STATIONARY TRANSFORMERS

THEORY, CONNECTIONS, OPERATION AND TESTING OF
CONSTANT-POTENTIAL, CONSTANT-CURRENT,
SERIES AND AUTO TRANSFORMERS,
POTENTIAL REGULATORS,
ETC.

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PREFACE.

Although much has been written on the fundamental principles of transformers, there has been little published concerning their connection, installation and operation. It was this lack of easily available information and the widespread desire of operators and engineers in the field to possess such information, that led the author to put in type these notes, which had been written up in the course of a number of years of experience in the field.

A working knowledge of the fundamental principles of electrical engineering is presupposed, and for this reason the treatment does not go into the whys and wherefores very deeply, but simply states the facts in as few words as possible. To aid in understanding quickly the phase relations and relative values of the various e.m.fs. and currents involved in a given system, vector diagrams are given with all diagrams of circuit connections.

Baramulla, Kashmir, India, W. T. TAYLOR.
December, 1908.

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Stationary Transformers

CHAPTER I.

INTRODUCTION.

The development of the alternating-current transformer dates back about 25 years. At that time very little was known regarding design for operation at high voltages, and the engineer of the present day can scarcely realize the difficulties encountered in the construction of the early transformers.

The high-voltage transformer made long-distance transmission work possible, and the increased distances of transmission stimulated the design of large transformers. In the early days of transformer development as many as 15 to 20 transformer secondary windings have been connected in series to facilitate the operation of a long-distance transmission system. The maximum rating of each transformer being not greater than 10 kw. However, a method of constructing large transformers has been devised by which an enormous amount of power may be transformed in a single unit. Such designs embody principles

of insulation for high voltages and various methods for maintaining a low operating temperature. Ten years ago a 500-kilowatt unit was considered to be a large size of transformer. The history of ten years development has shown a most interesting process of evolution: it has marked more than a tenfold increase in size up to the present day.

The alternating-current transformer is a piece of apparatus used for transforming alternating currents and voltages from one value to another.

The transformer consists primarily of three parts: the primary winding, the secondary winding and the iron core. The primary winding is connected in one circuit, the secondary in another and the core forms a magnetic circuit which links the two together.

The principle of the constant-potential transformer is easily explained if we neglect the slight effects of resistance drop in the windings, leakage of magnetic flux, and the losses. The primary winding is connected to a source of e.m.f., which connection would constitute a practical short-circuit were it not for the periodic changing in value which permits the flux produced by the current to generate a counter e.m.f. which will hold the current down to a value just sufficient to produce that value of flux necessary to generate an e.m.f. in the primary which is equal and opposite to the impressed e.m.f. This same flux is surrounded by the turns of the secondary winding and the same e.m.f. is generated in each turn

of wire whether primary or secondary. If E_1 is the impressed e.m.f.

$$\frac{E_1}{N_1} = e = \text{e.m.f. per turn,}$$

wherein N_1 is the number of primary turns. Then if N_2 is the number of secondary turns,

$$E_2 = N_2 e = \text{secondary e.m.f.}$$

and $$\frac{N_1}{N_2} = \frac{E_1}{E_2} = \text{ratio of transformation.}$$

When N_1 is greater than N_2, the transformer is called a " step-down transformer " and when N_1 is less than N_2 it is called a " step-up transformer."

The reader will understand that a step-up transformer is likewise a step-down transformer, or vice versa. The primary is the winding upon which the e.m.f. is impressed.

The electrical characteristics of a transformer are mostly dependent upon the quality, arrangement and proportion of the iron and copper that enter into its construction. The losses are of two kinds: the copper loss, due to the current through the coils; and the iron loss, caused by the reversing of the magnetic flux in the core. These losses appear as heat, and suitable means must be provided for the disposal of this heat.

A general description of the usual form of internal construction employed in high-tension transformers is somewhat as follows, however, certain deviations are sometimes made from this

form to accommodate the different cooling and insulating mediums.

The transformer windings are composed of a number of thin, flat coils placed side by side and separated by insulating material. The coils are made up of cotton-insulated rectangular wire, usually with but one turn per layer. After winding they are dried in a vacuum oven at a comparatively high temperature to abstract all the moisture, and then treated with a compound which prevents the re-absorption of moisture and adds greatly to their mechanical strength.

The treating process is repeated many times to insure a heavy, uniform waterproof coating, and after this treatment the coils are wrapped with insulating material and assembled with suitable ventilating ducts and insulating barriers between them. The ventilating ducts permit the cooling medium, oil or air, to come into close proximity to all parts of the winding and thus prevent undue local heating. The subdivision of the coils permits the interlacing of primary and secondary windings, which is an arrangement essential to close regulation of the transformer, especially when inductive loads, such as motors or arc lamps are supplied.

While the quality, arrangement and proportion of the iron and copper is one of the essentials in transformer design, the proper selection, treatment and arrangement of the insulating material requires even greater skill and wider knowledge

than does the proportioning of copper and iron. A transformer will not operate without sufficient insulation, but the less space occupied by this insulation the more efficient will be a transformer, with a given amount of iron and copper. After the coils have been properly insulated and assembled, the iron core or shell is built up about the coils, and ventilating ducts are provided at frequent intervals throughout the structure. When the laminations are all in place, the iron castings are put on and the core or shell structure is bolted up solidly.

In the design of successful transformers, the folowing equations are found reliable:

Let N = Total number of turns of wire in series.
ϕ = Total magnetic flux.
A = Section of magnetic circuit in square inches.
f = Frequency in cycles in seconds.
B = Lines of force per square inch.
E = Mean effective e.m.f.

$$4.44 = \frac{2\pi}{\sqrt{2}} = \sqrt{2} \times \pi$$

then
$$E = \frac{4.44\, f\, \phi\, N}{10^8} \tag{1}$$

Equation (1) is based on the assumption of a sine wave of e.m.f., and is much used in the design of transformers.

If the volts, frequency, and number of turns are known, then we have

$$\phi = \frac{E \times 10^8}{4.44 \times f \times N} \tag{2}$$

If the volts, frequency, cross-section of core, and density are known, we have:

$$N = \frac{E \times 10^8}{4.44 \times f \times B'' \times A} \tag{3}$$

Magnetic densities of transformers vary considerably with the different frequencies and different designs.

Current densities employed in transformers vary from 1,000 to 2,000 circular mils per ampere.

The **efficiency** of a transformer at any load is

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{core loss} + \text{copper loss}}$$

In the case of ordinary transformers with no appreciable magnetic leakage, the core loss is practically the same from no-load to full load. The only tests required, therefore, in order to obtain the efficiencies of such transformers at all loads, with great accuracy, are a single measurement by wattmeter of the watts lost in the core, with the secondary on open circuit; and measurements of the primary and secondary winding resistances, from which the $I^2 R$ watts are calculated for each particular load. The core loss which is made up of the hysteresis loss and eddy-current loss, re-

mains practically constant in a constant-potential transformer at all loads. In the case of constant-current transformers and others having considerable magnetic leakage when loaded, this leakage often causes considerable loss in eddy currents in the iron, in the copper, and in the casting or other surrounding metallic objects. It should be borne in mind that the efficiency will also depend on the frequency and the wave-form and that the iron core may age; that is to say, the hysteresis coefficient may increase after the transformer has been in use some time. As regards the efficiency of distribution by transformers, it is recommended that the substation method is far in advance of the small house transformers.

Generally speaking, the efficiency of a transformer depends upon the losses which occur therein, and is understood to be the ratio of its net output to its gross power input, the output being measured with non-inductive load. The point of most importance in a transformer is economy in operation, which depends not only upon the total losses, but more particularly upon the iron or core loss. For example, taking two transformers with identical total losses, the one showing the lower iron loss is to be preferred, because of the greater all-day efficiency obtained, and the resulting increase in economy in operation. This loss represents the energy consumed in applying to the iron the necessary alternating magnetic flux, and is a function of the quality of the iron and the

transformer is known as the copper loss. This loss is the sum of the $I^2 R$ losses of both the primary and secondary windings, and the eddy-current loss in the conductors. In well-designed transformers the eddy-current loss in the conductors is negligible, so that the sum of the $I^2 R$ losses of primary and secondary can be taken as the only copper loss in the transformer.

The copper loss occurs only when the transformer is loaded, and while it may be considerable at full load it decreases very rapidly as the load falls off. As the transformer is seldom operated at full load, and in many cases supplies only a partial load for a few hours each day, the actual watt-hours of copper loss is far below the actual watt-hours of iron loss. However, for equal full-load efficiencies, the transformer having equal copper and iron losses is cheaper to manufacture than one in which the iron loss is reduced, even though the copper loss is correspondingly increased.

The ability of a transformer to deliver current at a practically constant voltage regardless of the load upon it, is a very highly important feature. By the use of conductors of large cross-section and by the proper interlacing of primary and secondary coils, an extremely close regulation may be obtained with loads of all power-factors, which tends to lengthen the life of lamps and to improve the quality of the light.

In well-designed transformers, low core loss and

good regulation are in direct opposition to one another when both are desired in the highest degree. The regulation of a transformer is the ratio of the rise of secondary terminal voltage from full load to no-load, at constant primary impressed terminal voltage, to the secondary terminal voltage. In addition to the vastly improved service, it is possible to adopt the efficient low-consumption lamp, when the transformers in use maintain their secondary voltage at a practically constant value when the load goes on or off. While so few central stations are able to keep their voltage constant within 2 per cent. it may be concluded that at present the point of best practical regulation on transformers from about 5 kw. up, lies between the values of 1.75 per cent. to 2.00 per cent.

Regulation is a function of the ohmic drop and the magnetic leakage. To keep the iron loss within necessary limits and at the same time secure a good regulation is an interesting problem. We may reduce the resistance of the windings by using fewer turns of wire, but with fewer turns the iron is compelled to work at a higher flux density, and consequently with an increased loss. If we adopt a larger cross-section to reduce the flux density we need a greater length of wire for a given number of turns which thus gives an increase in resistance. The remaining expedient only is to use a larger cross-section of copper, while keeping down the flux density by employing a sufficient number of turns,

to secure the low resistance necessary for good regulation. For ordinary practice the regulation of a transformer for non-inductive loads may be calculated as follows:

$$\% \text{ regulation} = \frac{\% \text{ copper loss} - (\% \text{ reactance drop})^2}{200}$$

For inductive loads the regulation may be calculated by the following equation:

$$\text{Per cent. regulation} = \frac{\text{per cent. reactance drop}}{\operatorname{Sin}\theta} + \frac{\text{per cent. resistance drop}}{\operatorname{Cos}\theta}$$

wherein θ is the angle of phase displacement between the current and the e.m.f.

Regulation on inductive loads is becoming more important as the number of systems operating with a mixed load (lamps and motors) is constantly increasing. Many transformers while giving fair regulation on non-inductive loads, give extremely poor regulation on inductive loads.

For various reasons the temperature rise in a transformer is limited. The capacity for work increases directly as the volume of material, and the radiating surface as the square of the dimensions; therefore, it is evident that the capacity for work increases faster than the radiating surface.

The amount of heat developed in a transformer depends upon its capacity and efficiency. For instance, in a 500-kw. transformer of 98 per cent. efficiency there is a loss at full load of about 7.5

kw.; and since this loss appears as heat, it must be disposed of in some way, or the temperature of the transformer will rise until it becomes dangerously high. This heat may be removed in several ways; by ample radiation from the surface of the tank or case in which the transformer is operated; by the circulation of water through pipes immersed in oil; or by the constant removal of the heated oil and its return after being cooled off.

The determination of the temperature may be made by thermometer or by the measurement of resistance. High temperature causes deterioration in the insulation as well as an increase in the core loss due to ageing. The report of the Standardization Committee of the American Institute of Electrical Engineers specifies that the temperature of electrical apparatus must be referred to a standard room temperature of 25 degrees centigrade, and that a correction of one-half per cent. per degree must be made for any variation from that temperature, adding if less and subtracting if more.

The temperature rise may be determined by the change of resistance, using the temperature coefficient 0.39 per cent. per degree from and at zero degrees.

A transformer may have a very low iron loss, excellent regulation, and proper temperature rise, yet if its insulation is weak or defective, the transformer fails in the one duty above all others for which it is designed.

The National Board of Fire Underwriters specify that the insulation of nominal 2,000-volt transformers when heated shall withstand continuously for one minute a difference of potential of 10,000 volts (alternating) between primary and secondary coils and the core and a no-load run of double voltage for 30 minutes.

All transformers should be subjected to insulation tests between the primary and secondary, and the secondary and core. A transformer may have sufficient strength to resist the strain to which it is constantly subjected, and yet due to an imperfection in the insulation break down when subjected to a slight over-voltage such as may be caused by the opening of a high-power circuit. The application of a high-potential test to the insulation will break down an inferior insulation, or a weak spot or part of the structure in the insulation. The duration of the test may vary somewhat with the magnitude of the voltage applied to the transformer. If the test be a severe one, it should not be long continued, for while the insulation may readily withstand the application of a voltage five or even six times the normal strain, yet continued application of the voltage may injure the insulation and permanently reduce its strength.

In studying the performance of transformers it is convenient to use graphical methods. The graphical method of representing magnitudes varying in accordance with the sine law has been found to be a very simple one for making clear

the vector relations of the various waves to one another.

The principle of this method is shown in Fig. 1, where the length of the line *o e* represents the magnitude of the quantity involved, and the angle *e o x* $= \theta$ represents its phase position either in time or space.

In an alternating-current circuit the relation

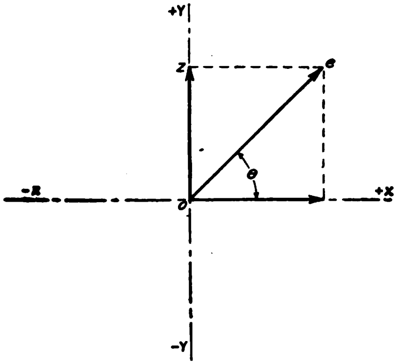


Fig. 1.—Vector diagram.

between the most important quantities may be represented by the method above mentioned. When such diagrams are used to represent voltages or currents, the length of the lines represents the scale values of the quantities, while the angles between the lines represent the angle of phase difference between the various quantities. The diagrams being constructed from data available in each case. The diagram below represents

a circuit containing resistance and inductive reactance. Since the $I R$ drop is always in phase with the current and the counter e.m.f. of self-inductance in time-quadrature with the current which produces the m.m.f., these two magnitudes will be represented by two lines, $o\ e_1$ and $o\ e_3$, at

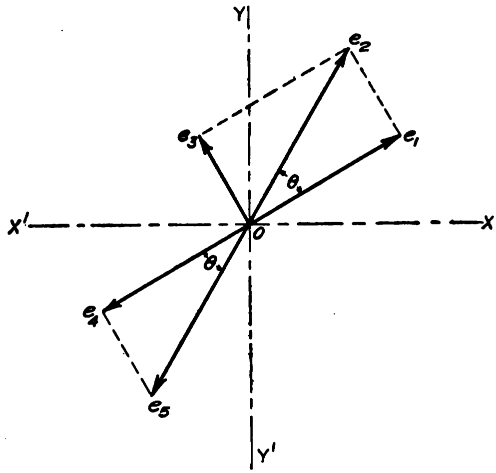


FIG. 2.—Vector diagram of a transformer, assuming an inductive load.

right angles to each other; their sum being represented by $o\ e_2$, which represents the resultant value of these two e.m.fs., and is, therefore, equal and opposite to the e.m.f., e_s, which must be impressed on the circuit to produce the current, I, against the counter e.m.f. of self-inductance,

$2\pi f L I$, and the counter e.m.f. of resistance, $I R$. Therefore, by the properties of the angles,

$$e_5^2 = (I R)^2 + (2\pi f L I)^2$$

The angle of lag of the current behind the e.m.f. is shown as the angle between the lines representing the resistance e.m.f. and that representing the resultant of the resistance and the reactance e.m.f. Since the resistance component of the impressed e.m.f. is in phase with the current and differs 180 degrees in phase from the resistance e.m.f., its position will be that shown by the line $o\, e_4$, and the angle between that line and $o\, e_5$ is the angle of lag.

The tangent of the angle, θ, is equal to $\dfrac{o\, e_3}{o\, e_1}$.

$$o\, e_3 = 2\pi f L I \text{ and } o\, e_1 = I R,$$

$$\text{or } \tan\theta = \frac{2\pi f L I}{I R} = \frac{2\pi f L}{R}$$

It is very evident that when the resistance is large compared with the reactance, the angle of time-lag is practically zero. If the reactance is very large compared with the resistance, the angle of lag will be almost 90 time-degrees; in other words, the current is in quadrature with the e.m.f.

A problem which can always be solved by the use of transformers, is the converting of one polyphase system into another, since in the original system there must be at least two components of by e.m.f., which are displaced in time-phase and by

varying the values of these components a resultant of any desired phase can be obtained. In phase-spliting devices using inductive or condensive reactance, an e.m.f. in quadrature with the impressed e.m.f. is obtained from the reactive drop of the current through an inductive winding, or a condenser, and the necessary energy is stored as magnetic energy, $\frac{I^2 L}{2}$, in the core of the winding, or as electrostatic energy, $\frac{E^2 C}{2}$, in the dielectric of the condenser; but such devices are of little practical use.

CHAPTER II.

SINGLE-PHASE TRANSFORMER MANIPULATIONS.

There are a number of different ways of applying transformers to power and general distribution work, some of which are:

Single-phase.
Two-phase.
Three-phase delta.
Three-phase star.
Three-phase tee.
Three-phase open delta.
Three-phase star and delta.
Three-phase to two-phase.
Three-phase to single-phase.
Three-phase to six-phase.

The two principal precautions which must be observed in connecting two transformers, are that the terminals must have the same polarity at a given instant, and the transformers should have practically identical characteristics. As regards the latter condition, suppose a transformer with a 2 per cent. regulation is connected in parallel with one which has 3 per cent. regulation; at no load the transformers will give exactly the same e.m.f. at the terminals of the secondary, but at full load one will have a secondary e.m.f. of, say, 100 volts, while the other has an e.m.f. of 99 volts. The

result is that the transformer giving only 99 volts will be subject to a back e.m.f. of one volt, which will disturb the phase relations and lower the power-factor efficiency and combined capacity; in which case it is much better to operate the secondaries of the two transformers separately. In order to determine the polarity of two transformers proceed with the parallel connection as if everything were all right, but connect the terminals together through two small strips of fuse wire,

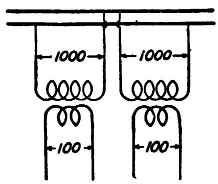


FIG. 3.—Straight connection of two ordinary single-phase transformers.

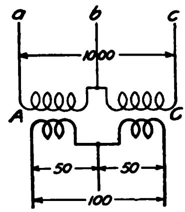


FIG. 4.—Single-phase transformer with primary and secondary coils both in series.

then close the primary switch. If the fuse blows, the connections must be reversed; if it does not, then the connections may be made permanent.

Fig. 3 shows the way in which two ordinary single-phase transformers are connected.

Fig. 4 shows one transformer which has two secondary coils connected in series. If this transformer be of the core type and the two coils arranged on different limbs of the core, it will be advisable to have the fuse in the middle wire con-

siderably smaller than those on the two outside wires. The reason for this is, that should one of the fuses on the outside circuits blow, say, for instance the fuse on leg A, the secondary circuit through this half-section will be open-circuited, and the primary coil corresponding to this section will have a greater impedance than the other half of the coil, the inductance of which will be neutralized by the load on the other half of the secondary coil. The result will be that the counter e.m.f. of the primary section, A, will be greater than that of section C, because the two sections are in series with each other, and the current must be the same in both coils, therefore, the difference of potential between the primary terminals, A, will be greater than that between the primary terminals of C, consequently the secondary voltage of C will be greatly lowered.

Manufacturers avoid the above mentioned disadvantage by dividing each secondary coil into two sections, and connecting a section of one leg in series with a section of the coil on the other leg of core, so that the current in either pair of the secondary windings will be the same in coils about both legs of the core.

Transformers are made for three-wire service having the windings so distributed that the voltage on the two sides will not differ more than the regulation drop of the transformer, even with one-half the rated capacity of the transformers all on one side, with ordinary distribution of load

the voltage will be practically equal on the two sides.

Fig. 5 shows a single-phase transformer with two coils on the primary, and two coils on the secondary. The primaries are shown connected in parallel across the 1,000-volt mains, and the secondaries are also connected in parallel.

To obtain a higher secondary voltage the coils may be connected as shown in Fig. 6. In this

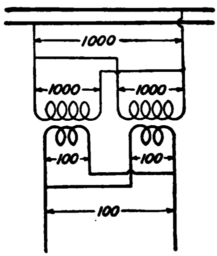


FIG. 5.—Transformer with primary and secondary windings both in parallel.

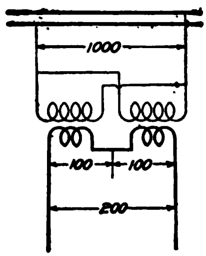


FIG. 6.—Transformer with primary windings connected in parallel and secondary windings in series.

case the primary coils are connected in parallel, and the secondary coils are connected in series. The difference of potential across the two leads, with the primaries connected in parallel and the secondaries connected in series will be 200 volts, or 100 volts per coil.

If we should invert the arrangement shown in

NOTE—For convenience all ratios of transformation will be understood to be ten to one, (10 to 1).

Fig. 6 by connecting the primary coils in series, and connecting the secondary coils in parallel, we shall obtain a secondary voltage of 50, as represented in Fig. 7.

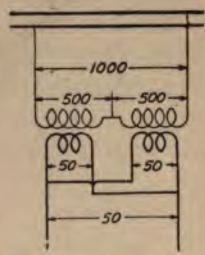


FIG. 7.—Transformer with primary windings connected in series and secondary windings in parallel.

In Figs. 8 and 9 are represented a right and a wrong way of connecting transformers in series or parallel, just as the case may be. The connections shown in Fig. 8 represent the right way of connecting two transformers in parallel, or in series, the solid lines showing the series connection and the dotted lines the parallel connection.

The connections shown in Fig. 9 are liable tc

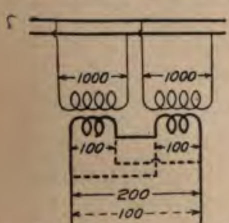


FIG. 8.—The right way of connecting single-phase transformers in parallel.

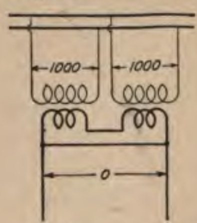


FIG. 9.—The wrong way of connecting single-phase transformers in parallel.

happen when the transformers are first received from the factory. Through carelessness, the leads are often brought out in such a manner as

to short-circuit the two coils if connected as shown. In this case the sudden rush of current in the primary windings would burn out the transformer if not protected by a fuse.

The three-wire arrangement shown in Fig. 10 differs in every respect from the three-wire system represented in Figs. 4 and 6. The two outside wires receive current from the single-phase transformer, and the center, or neutral, wire is taken

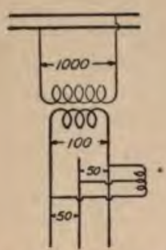


FIG. 10.—Three-wire secondary distribution.

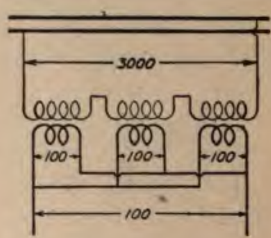


FIG. 11.—Three 1000-volt transformers connected in series to a 3000-volt circuit.

care of by a balancing transformer connected up at or near the center of distribution. The balancing transformer need only be of very small size, as it is only needed to take care of the variation of load between the two outside wires.

It is sometimes desirable to use a much higher voltage than that for which the transformers at hand have been designed, and to attain this, the secondary wires of two or more transformers may be connected in parallel, while the primary wires

may be connected in series with the source of supply.

This manner of connecting transformers is shown in Fig. 11. It, however, involves a high-voltage strain inside the separate transformers, between the high- and low-tension windings, and is therefore used only in special cases of necessity.

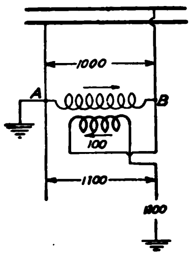


FIG. 12.—Connection between primary and secondary windings, which gives 1100 volts across the secondary distribution wires. Boosting transformer.

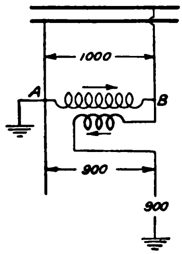


FIG. 13.—Connection between primary and secondary windings from which we obtain 900 volts. Lowering transformer.

While it is possible to insulate for very high voltages, the difficulties of insulation increase very rapidly as the voltage is raised, increasing approximately as the square of the voltage.

Consider the case of a single-phase transformer as shown in Fig. 3. There is evidently a maximum strain of 1,000 volts from one high-tension line wire to the other, and a strain of 500 volts from

one line wire to ground, if the circuits are thoroughly insulated and symmetrical. The strain between high-tension and low-tension windings is equal to the high-tension voltage, plus or minus the low-tension voltage, depending upon the arrangement and connection of the coils. With the arrangement shown in Fig. 12, it is quite possible to obtain 1,100 volts between the wire, *B*, and ground, and the first indication of any such trouble is likely to be established by a fire, or some person coming in contact with a lamp socket, or other part of the secondary circuit that is not sufficiently insulated.

Should a ground exist, or in other words, a short-circuit between the high-tension and low-tension windings, it will, in general, blow fuses, thus cutting the transformer out of service; or the voltage will be lowered to such an extent as to call attention to the trouble.

Fig. 13 represents an arrangement of primary and secondary circuits that may accidentally be made. These conditions immediately establish a potential difference of 900 volts.

CHAPTER III.

TWO-PHASE TRANSFORMER CONNECTIONS.

So far as transformers are concerned in two-phase distribution, each circuit may be treated independently of the other as shown in Fig. 14, which is connected as though each primary and secondary phase were only a straight, single-phase system. One transformer is connected to one primary phase and supply one secondary phase, independent of the other phase, and the other transformer is connected to the other primary phase, supplying the other secondary phase.

In the two-phase system the two e.m.fs. and currents are 90 time-degrees or one-fourth of a cycle apart. The results which may be obtained from various connections of the windings of single-phase transformers, definitely related to one another in point of time, may be readily determined by diagrams.

The vector diagram in which e.m.fs. and currents are represented in magnitude and phase by the length and direction of straight lines, is a common method dealing with alternating-current phenomena. To secure a definite physical conception of such diagrams, it is useful to consider the lines representing the various e.m.fs. and currents, as also representing the windings which are drawn to have angular positions corresponding

to angles between the lines in the diagrams; the windings are also considered to have turns proportional in number to the length of the corresponding lines and to be connected in the order in which the lines in the diagrams are connected.

The method of connecting two transformers to a four-wire, two-phase system is shown in Fig. 15. Both phases, as will be seen, are independent in that they are transformed in separate transformers.

A method of connection commonly used to obtain economy in copper is that shown in Fig. 15.

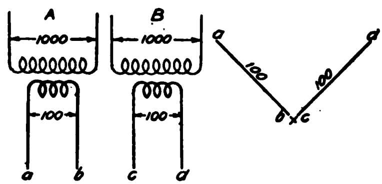


FIG. 14.—Two-phase four-wire arrangement.

where the primaries of the transformers are connected independently to the two phases, and the secondaries are changed into a three-wire system, the center, or neutral wire being about one-half larger than each of the two outside wires.

So long as the two transformers are not connected in parallel it makes no difference which secondary wire of any one of the two transformers is connected to a given secondary wire. For example: It is just as well to connect the two outside wires, *a* and *b*, together, as it is to con-

nect a' and b' as shown in Fig. 15. However, it makes no difference which two secondary wires are joined together, so long as the other wires of each transformer are connected to the outside wires of the secondary system. The two circuits being 90 time-degrees apart, the voltage between a and b is $\sqrt{2} = 1.141$ times that between any one of the outside wires and the neutral, or common return wire. The current in c is $\sqrt{2} = 1.141$ times that in any one of the outside wires. Each transformer takes its individual phase as in the four-wire system, the voltage in no way being affected by the modification of the phase relations.

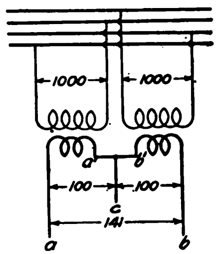


FIG. 15.—Two-phase four-wire primary with three-wire secondary.

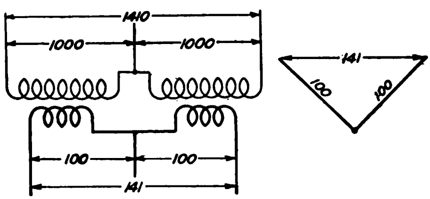


FIG. 16.—Two-phase three-wire primary with three-wire secondary.

Fig. 16 shows another method of connecting transformers, where the common return is used on both primary and secondary. With this method,

there is an unbalancing of both sides of the system on an induction-motor load, even if all the motors on said system should be of two-phase design. The unbalancing is due to the e.m.f. of self-induction in one side of the system being in phase with the effective e.m.f. in the other side, thus affecting the current in both circuits.

Another arrangement is to connect the middles of the two transformer secondaries, as shown in Fig. 17. This method gives two main circuits,

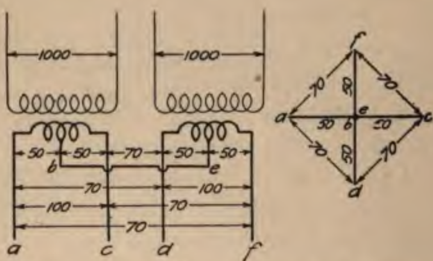


FIG. 17.—Two-phase star or four-phase connection.

a c and *d f*, and four side circuits, *a d*, *d c*, *c f*, and *f a*. The voltage of the two main circuits, between *d* and *f* is 100, and between *a* and *c* is 100. But the voltage across any one of the side circuits is one-half times that in any one of the main circuits, times the square root of two, or $50 \times \sqrt{2} = 70$ volts.

Another method shown in Fig. 18, commonly called the five-wire system, is accomplished by connecting the secondaries at the middle, similar

to the arrangement in Fig. 17, and bringing out an extra wire from the center of each transformer.

The difference of potential between *a* and *e* will be $100\times\sqrt{2}=141$ volts, that across *b d*

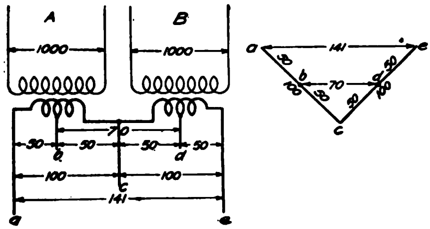


FIG. 18.—Two-phase five-wire secondary distribution.

will be $50\times\sqrt{2}=70$ volts, and that across any one of the main circuits will be 100 volts.

Another very interesting two-phase transformation may be obtained from two single-phase

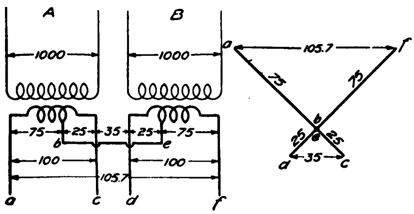


FIG. 19.—Two-phase multi-wire distribution.

transformers by simply connecting the two secondary windings together at points a little to one side of the center of each transformer, (see Fig. 19). There are to be obtained $75\times\sqrt{2}=106$ volts

between a and f; $\sqrt{75^2+25^2} = 79$ volts between a and d, and c and f; $25 \times \sqrt{2} = 35$ volts between d and c, and 100 volts across each of the secondary windings.

It is possible by a combination of two single-phase transformer connections, to change any polyphase system into any other polyphase system, or to that of a single-phase system.

The transformation from a two-phase to a single-phase system is effected by proportioning the windings; or one transformer may be wound for a

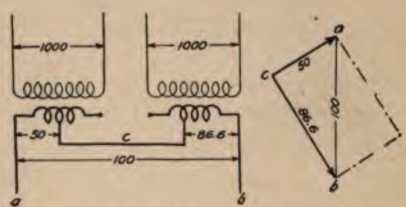


FIG. 20.—Two-phase to single-phase distribution.

ratio of transformation of 1,000 to 50; the other a ratio of 1,000 to 86.6, or $\left(\frac{\sqrt{3}}{2}\right)$. The secondary of this transformer is connected to the middle of the secondary winding of the first.

In Fig. 20, $a\,c$ represents the secondary potential from a to c in one transformer. At the angle of 90 degrees to $a\,c$ the line, $c\,d$, represents in direction and magnitude the voltage between c and b of the other transformer. Across the termi-

nals, *a c*, *c b*, and *a b*, it follows that three e.m.fs. will exist, each differing in direction and value. The e.m.f. across *a b* being the resultant of that in *a c* and *c b* or 100 volts.

CHAPTER IV.

THREE-PHASE TRANSFORMATION SYSTEMS.

In considering the question of three-phase transformation we have to deal with three alternating e.m.fs. and currents differing in phase by 120 degrees, as shown in Fig. 21.

One e.m.f. is represented by the line, $A B$, another by the line, $B C$, and the third by the line, $C A$. These three e.m.fs. and currents may be carried to three independent circuits requiring six wires, or a neutral wire, or common return wire may be used, where the three ends are joined together at x. The e.m.f. phase relations are represented diagrammatically by the lines, $a x$, $b x$, and $c x$; also, $A B$, $B C$, and $C A$. The arrows only indicate the positive directions in the mains and through the windings; this direction is chosen arbitrarily, therefore, it must be remembered that these arrows represent not the actual direction of the e.m.fs. or currents at any given instant, but merely the directions of the positive e.m.fs. or currents *i.e.*, the positive direction through the circuit. Thus, in Fig. 21 the e.m.fs. or currents are considered positive when directed from the common junction x towards the ends, a b c.

In passing through the windings from a to b, which is the direction in which an e.m.f. must be generated to give an e.m.f. acting upon a receiving

circuit from main *a* to main *b*, the winding, *a*, is passed through in a positive direction, and the winding, *b*, is passed through in a negative direction; similarly the e.m.f. from *b* to *c*, and the e.m.f. from main *c* to *a*. The e.m.f. between *a* and *b* is 30 degrees behind *a* in time-phase, and its effective value is

$$2\,E \cos 30^\circ = \sqrt{3}\,E;$$

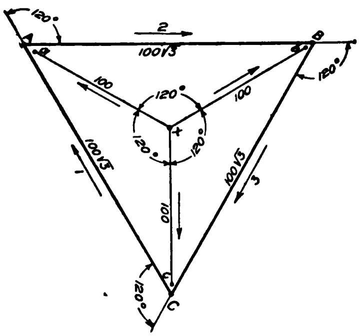


FIG. 21.—Graphic representation of three-phase currents and e.m.fs.

where E is the value of each of the e.m.fs. *a b*, and *c*.

With this connection the e.m.f. between any two leads, *a b*, *b c*, or *a c*, is equal to the e.m.f. in each winding, *a x*, *b x*, or *c x* multiplied by the square root of three.

For current relations we see in Fig. 21 that a positive current in winding 1 produces a positive

current in main A, and that a negative current in winding 2 produces a positive current in main A; therefore, the instantaneous value of the current in main A is $I_1 - I_2$, where I_1 is the current in winding 1, and I_2 is the current in winding 2. Similarly, the instantaneous value of the current in main B is $I_2 - I_3$, and in main C, it is $I_3 - I_1$. The mean effective current in main A is 30 degrees behind I_1 in phase; and its effective value is the square root of three times the current in any of the different phases; so that with this connection the current in each main is the square root of three times the current in each winding.

When the three receiving circuits $a\ b\ c$ are equal in resistance and reactance, the three currents are equal; and each lags behind its e.m.f., $a\ b$, $b\ c$, and $a\ c$, by the same amount, and all are 120 time-degrees apart. The arrangement shown in Fig. 21, by the lines, a, b, and c, and is called the "Y" or star connection of transformers. Each of these windings has one end connected to a neutral point, x, the three remaining ends, $a\ b\ c$, commonly called the receiving ends, are connected to the mains. The e.m.f. between the ends, or terminals of each receiving circuit is equal to $\sqrt{3}\ E$, where E is the e.m.f. between $a\ x$, $b\ x$, and $c\ x$. The current in each receiving circuit is equal to the current in the mains, $a\ b\ c$.

The resistance per phase cannot be measured directly between terminals, since there are two windings, or phases in series. Assuming that all

the phases are alike, the resistance per phase is one-half the resistance between terminals. Should the resistances of the phases be equal, the resistance of any phase may be measured as follows:

The resistance between terminals $a\,b$ is:

$$\text{Resistance of } a\,b = R_3 + R_1.$$

The resistance between terminals $b\,c$ is:

$$\text{Resistance of } b\,c = R_1 + R_2.$$

The resistance between terminals $a\,c$ is:

$$\text{Resistance of } a\,c = R_3 + R_2.$$

Therefore:

$$R_3 = \frac{\text{Res. } a\,b - \text{Res. } b\,c + \text{Res. } a\,c}{2},$$

$$R_1 = \frac{\text{Res. } b\,c - \text{Res. } a\,c + \text{Res. } a\,b}{2},$$

$$R_2 = \frac{\text{Res. } a\,c - \text{Res. } a\,b + \text{Res. } b\,c}{2},$$

The method of connecting three-phase circuits shown in Fig. 21, where the windings, 1, 2 and 3, are connected in series at A, B and C, is called the delta connection. In this connection the e.m.f. on the receiving circuit is the same as that on the mains; and the current on each receiving circuit is equal to $\sqrt{3}$ times that in any winding, or $\sqrt{3}\,I$, where I is the current in 1, 2, or 3.

Assuming that all phases are alike, the resistance per phase is equal to the ratio of 3 to 2 times $\frac{3}{2}$ the resistance between A and B. In a delta connec-

tion there are two circuits between A and C, one through phase 1, and the other through phases 2 and 3 in series. From the law of divided circuits we have the joint resistance to two or more circuits in parallel is the reciprocal of the sum of the reciprocals of the resistances of the several branches. Hence, $\frac{3R}{2}$ is the resistance per phase R being the resistance of one winding with two others in parallel. The ohmic drop from terminal to terminal with current I in the line, is

$$\text{Ohmic drop} = \frac{3}{2} I \times \text{R}.$$

To transform three-phase alternating current a number of different ways are employed, several of the arrangements are:

1. Three single-phase transformers connected in star or in delta.
2. Two single-phase transformers connected in open-delta or in tee.
3. One three-phase transformer connected in star or in delta.

With three single-phase transformers the magnetic fluxes in the three transformers differ in phase by 120 time-degrees.

With two single-phase transformers the magnetic fluxes in them differ in time-phase by 120 degrees or by 90 degrees according to the connection employed.

With the three-phase transformer there are

three magnetic fluxes differing in time-phase by 120-degrees.

The single-phase transformer weighs about 25 per cent. less than three separate transformers having the same total rating; its losses at full load are also about 25 per cent. less.

Two separate transformers, V-connected, weigh the same as three single-phase transformers for the same power transmitted; the losses are also equal.

A three-phase transformer weighs 16.5 per cent. less than three separate transformers; its losses are also 16.5 per cent. less.

It is considered that for transformation of three-phase power the three-phase transformer is to be preferred to any other combination method.

In America it is customary to group together single-phase transformers for use on polyphase circuits, while in Europe the polyphase transformer is exclusively employed. The relative merits of three-phase transformers and groups of three single-phase transformers, in the transmission and distribution of power, form a question that is capable of being discussed from various standpoints.

A popular argument in favor of the three-phase transformer is the greater compactness of the transformer unit; and the favorite argument against the three-phase transformer is that if it becomes disabled all three sides of the system must be put out of service by disconnecting the ap-

paratus for repair; whereas if a similar accident occurs to any one of three single-phase transformers in a delta-connected group, the removal of the defective transformer only affects one side of the system, and two-thirds of the total transformer capacity would go on working. The relative merits of the three-phase transformer and the combination of three single-phase transformers that may be employed for obtaining the same ser-

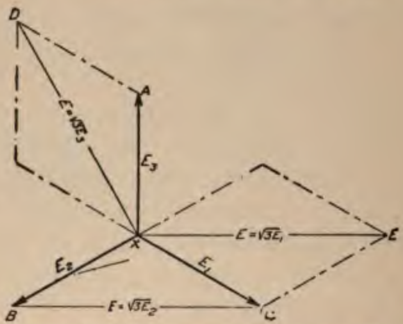


FIG. 22.—Graphic representation of three-phase e.m.fs.

vice are frequently discussed on the basis of the decrease in cost of the several types of transformers with increase in rating; and on such basis it has been shown that the three-phase transformer is the cheapest, while the other combinations are more expensive on account of requiring an equal or greater aggregate rating in smaller transformers. It should, however, be borne in mind that a three-phase transformer can never be so cheap or so efficient as a single-phase trans-

former designed along the same lines and wound for the same total output.

It is shown very clearly in Fig. 22 that a connection across the terminals, *B C*, *x E*, and *x D*, receives a voltage which is the resultant of two e.m.fs. differing in time-phase by 120 degrees; or the result from adding the e.m.fs. of E_3 and E_1 at 60 degrees, which is equivalent to $E_3\sqrt{3}$.

It is proved in Fig. 23, where one phase of a star-

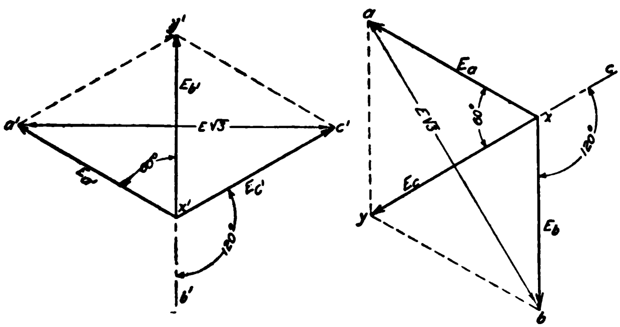


FIG. 23.—Vector sum of effective e.m.fs.

connected group of transformers is reversed, showing the resultant e.m.f., $x' y'$ and $x y$, which is equivalent to the component e.m.fs., $x c'$, $x a'$ and $x b$, $x a$; consequently the resultant of all three e.m.fs. is zero. This is in accordance with Kirchhoff's law which states that where an alternating-current circuit branches, the effective current in the main circuit is the geometric, or vector sum of the effective currents in the separate

branches. The modifications of the fundamental laws appertaining to this are discussed in many books treating alternating currents in theory, and the summary given here is for the purpose of comparison. However, it is noted in Fig. 23 that the phase relations between a' and b', b' and c', a and c and b and c have been changed from 120 degrees to 60 degrees by reversing phases b' and c. The pressure between a and b and a' and c' is $E\sqrt{3}$, showing their phase relations to be unchanged.

For example, in Fig. 23, considering only secondary coils of three single-phase transformers that are supposed to be connected in star, but as a matter of fact they are connected as shown, let us assume that E is equal to 100 volts:

(a) What is the voltage between terminals of E_a', E_c', and E_a, E_b, and E_c phases?

(b) What is the voltage between terminals a' and c', and a and b?

(c) What is the voltage across $a'\,y'$ and $y'\,c'$, also $a\,y$ and $y\,b$?

(a) The voltage acting on any of these windings is equal to $E\sqrt{3}$

$$100 \times \sqrt{3} = 173.2 \text{ volts.}$$

The voltage acting on E_a', E_b', etc., is

$$E_a' = \frac{1}{\sqrt{3}} \times 173.2 = 0.577 \times 173.2 = 100 \text{ volts.}$$

(b) The voltage between terminals a' and c', or

a and *b*, is equal to $\sqrt{3}$ times the voltage acting on E_a etc., or

$$E\sqrt{3} = 100 \times 173.2 = 173.2 \text{ volts.}$$

(c) It is evident that the two e.m.fs., $a'\,x'$ and $c'\,x'$, are equivalent to their resultant, $y'\,x'$, which is equal and opposite to $b'\,x'$; the dotted lines, $a'\,y'$

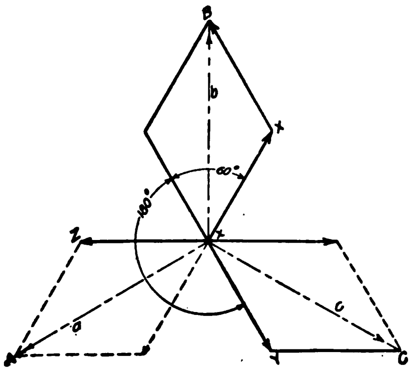


FIG. 24.—Geometric sum of three-phase currents.

and $y'\,c'$, are equal to E_a', E_b', etc., at 120 degrees apart; in other words,

$$E = a'\,y', \text{ etc.,} = \frac{1}{\sqrt{3}} \times 173.2$$
$$= 0.577 \times 173.2 = 100 \text{ volts.}$$

In Fig. 24 is shown a diagram of three-phase currents in which *x*, *y*, *z* are equal and 120 degrees apart, the currents in the leads, *a*, *b*, *c*, are 120

degrees apart and each equal to $\sqrt{3}$ times the current in each of the three circuits X, Y and Z.

The current in each lead is shown made up of two equal components which are 60 degrees apart.

As an example showing the use of Fig. 24, assume a circuit, of three single-phase transformers delta-connected. What is the current through

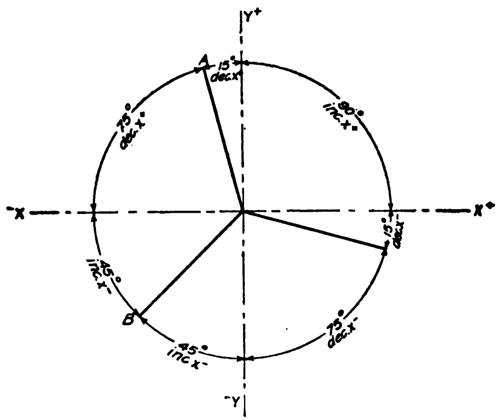


FIG. 25.—Geometric sum of e.m.fs. at any instant equal to zero.

the X-phase winding if the current in the b lead is 500 amperes?

Since one component, X, has in the lead the same sign as it has in its own transformer winding, and the other component, Y, has in the lead the opposite sign to that which it has in its own transformer winding, X, is represented in the lead by

the same vector as in its own transformer winding; while the other component, Y, is represented in the lead by a vector 180 degrees from that which represents it in its own circuit.

The instantaneous values of the currents in any one wire of a three-phase system is equal and opposite to the algebraic sum of the currents in the other two sides. Therefore, the algebraic sum of e.m.fs. or currents at any instant is equal to zero. This fact is shown in Fig. 25, the geometric sum of the three lines, A, B, C, being equal to zero at any instant.

Single-phase transformers may be connected to a three-phase system in any of the following manners:

Delta-star group with a delta-star.
Star-star group with a star-star.
Delta-delta group with a delta-delta.
Star-delta group with a star-delta.
Delta-star group with a star-delta.
Delta-delta group with a star-star.

It must, however, be remembered that it is impossible to connect the following combinations, because the displacement of phases which occurs, when an attempt is made to connect the secondaries, will result in a partial short-circuit.

Delta-star with a star-star.
Delta-delta with a star-delta.
Delta-star with a delta-delta.
Star-delta with a star-star.

Further mention will be made in a later part of this work of the methods of parallel operation as mentioned above.

As is well known there are four ways in which three single-phase transformers may be connected between primary and secondary three-phase circuits. The arrangements may be described as the delta-delta, star-star, star-delta, and delta-star.

In winding transformers for high voltage the

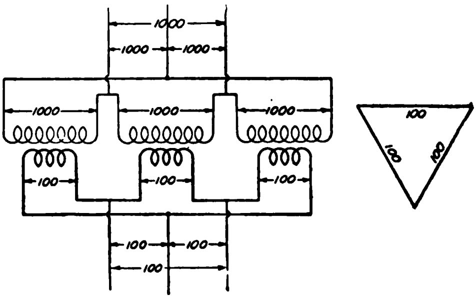


Fig. 26.—Delta-delta connection of transformers.

star connection has the advantage of reducing the voltage on an individual unit, thus permitting a reduction in the number of turns and an increase in the size of the conductors, making the coils easier to wind and easier to insulate. The delta-delta connection nevertheless has a distinct advantage over the star-star or star-delta arrangement, in that if one transformer of a group of three should become disabled, the two remaining ones will continue to deliver three-phase currents with

a capacity equal to approximately two-thirds of the original output of the group. Fig. 26 shows a delta-delta arrangement. The e.m.f. between the mains is the same as that in any one transformer measured between terminals. The current in the line is $\sqrt{3}$ times in any one transformer winding.

Each transformer must be wound for the full-line voltage and for 57.7 per cent. line current. The greater number of turns in the winding, together with the insulation between turns, necessitates a larger and more expensive coil than the star connection.

For many reasons the delta-delta connection is much preferable to the star, inasmuch as the arrangement is not affected even though one transformer may be entirely disconnected, in which case it is practically assumed that the two remaining transformers have exactly a carrying capacity of 85 per cent. of $\frac{2}{3} = 0.567$.

In a delta connected group of transformers the current in each phase winding is $\frac{I}{\sqrt{3}}$, I being the line current, and if a phase displacement exists, the total power for the three phases is expressed as $\sqrt{3} \times E \times I \times \text{Cos}\ \theta$.

As an example,—assume that the voltage between any two mains of a three-phase system is 1,000 volts; the current in the mains is 100 amperes, and the angle of time-lag is 45 degrees. It is required to find the e.m.f. acting on each phase, the current in each phase, and the output.

The e.m.f. on each phase of a delta-connected group of transformers is the same as that across the terminals of any one transformer. The line current is $\sqrt{3}$ times that in each transformer winding, or $\sqrt{3}\times 57.7 = 100$ amperes, therefore the current in each phase is $100\times\frac{1}{\sqrt{3}} = 57.7$ amperes. The output is $\sqrt{3}\ E\ I \operatorname{Cos}\theta =$

$$1.732\times 1{,}000\times 100\times .71 = 123 \text{ kw. approx.}$$

In the star-star arrangement each transformer

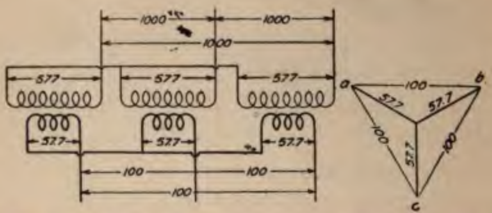


Fig. 27.—Star-star connection of transformers.

has one terminal connected to a common junction, or neutral point; the three remaining ends are connected to the three-phase mains.

The number of turns in a transformer winding for star connection is 57.7 per cent. of that required for delta connection and the cross-section of the conductors must be correspondingly greater. The star connection requires the use of three transformers, and if anything goes wrong with one of them the whole group becomes disabled.

The arrangement shown in Fig. 27, is known

as the " star " or " Y " system, and is especially convenient and economical in distributing systems, in that a fourth wire may be led from the neutral point of the three secondaries.

The voltage between the neutral point and any one of the outside wires is $\frac{1}{\sqrt{3}}$ of the voltage between the outside wires, namely

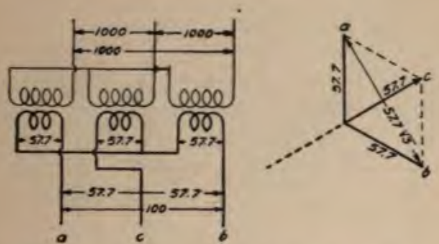


FIG. 28.—Star-star connection of transformers, one phase reversed.

$$1,000 \times \frac{1}{\sqrt{3}} = 1,000 \times 0.577 = 577 \text{ volts.}$$

The current in each phase of a star-connected group of transformers is the same as that in the mains.

Fig. 28 shows a star-star connection in which one of the secondary windings is reversed. It may be noted that the phase relations of phase *c* have changed the relations of *a c* and *b c* from 120 degrees to 60 degrees by the reversal of one trans-

former connection. The resultant e.m.fs., $a\,c$ and $b\,c$, are each $\frac{1}{\sqrt{3}} = 57.7$, which should be 100 volts—the voltage between a and b is $57.7\times\sqrt{3} = 100$. In star-connecting three single-phase transformers it is quite possible to have one of the transformers reversed as shown.

In the star-delta arrangement shown in Fig. 29

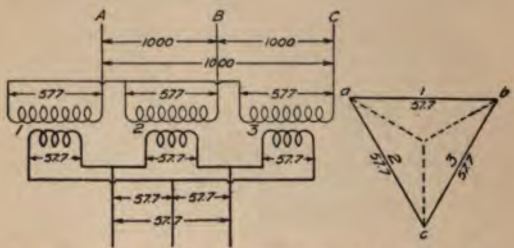


Fig. 29.—Star-delta connections of tranformers.

the ratio of transformation is $\frac{1}{\sqrt{3}}$, or 0.577 times the ratio of secondary to primary turns, and the e.m.f. acting on each secondary circuit is the same as that between the mains.

For example, let us assume that 1,000 volts are impressed on the primary mains. The voltage between any two secondary mains is the same as that generated in each transformer, namely, 57.7 volts, or $100\times\frac{1}{\sqrt{3}} = 57.7$ volts.

Fig. 30 shows a delta-star connection using three single-phase transformers. From the neutral point of the secondary star connection, a wire may be brought out, serving a purpose similar to that of the neutral wire in the three-wire Edison system, it being without current when the load is balanced. The ratio of transformation for the delta-star arrangement is $\sqrt{3}$, or 1.732 times the ratio of secondary to primary turns.

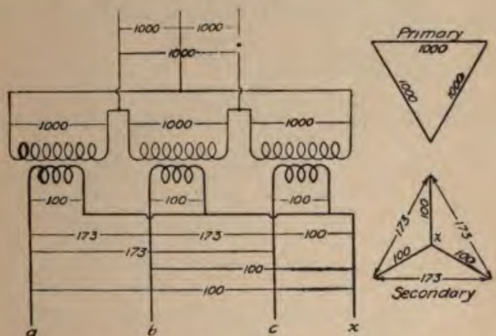


Fig. 30.—Delta-star four-wire connection of transformers.

The advantage of this secondary connection lies in the fact that each transformer need be wound for only 57.7 per cent., of the voltage on the mains.

In this arrangement, commonly called " V " or " open-delta " the voltage across the open ends of the two transformers is the resultant of the voltages of the other two phases; see Fig. 31. This method requires about 16 per cent. more trans-

former capacity than any of the previous three-phase transformations shown, assuming the same efficiency of transformation, heating, and total power transformed.

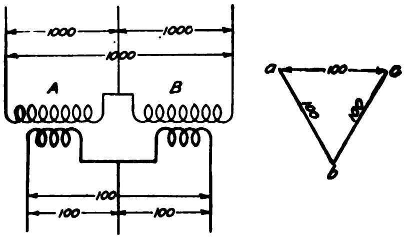


FIG. 31.—Open-delta or " V " connection of transformers.

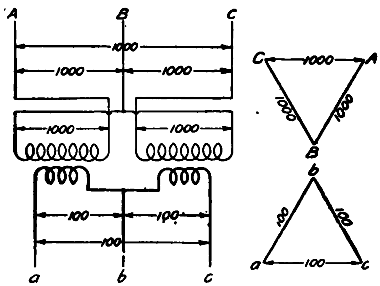


FIG. 32.—" V " connection of transformers with secondary windings connected in opposite direction.

With the open-delta method a slight unbalancing may exist, due to the different impedances in the middle main and the two outside mains, the impedance in the middle main being the algebraic sum of the impedances in the two outside mains.

The open-delta arrangement, where the primary is connected like that shown in Fig. 32, is in every respect equivalent to the open-delta connection represented in Fig. 31. The primaries are connected in a reverse direction, or 180 degrees apart in phase with the secondary.

The vector diagram shows the changed phase relations of primary to secondary. By connecting the two single-phase transformers in the opposite direction, that is to say, connecting the

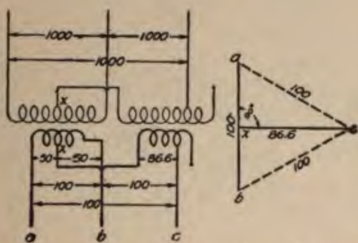


FIG. 33.—Tee or " T " connection of transformers.

secondary like that of the primary, and the primary like that of the secondary, we obtain the same transformation characteristics.

Like that of the open-delta arrangement the tee method requires only two single-phase transformers.

As regards the cost of the equipment and the efficiency in operation the tee arrangement is preferable to either the open-delta, the star or the delta methods.

The tee arrangement is represented in Fig. 33.

The end of one transformer is connected to the middle of the other.

The number of turns on $a\ b$ is $\frac{2}{\sqrt{3}} = 1.16$ times the number of turns on $x\ c$. Its ability to maintain balanced phase relations is much better than the open-delta arrangement, and in many cases it is preferable to either the star or delta methods of connecting three single-phase transformers.

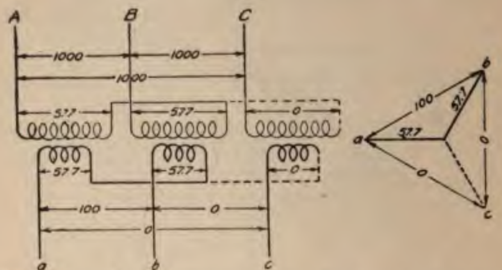


FIG. 34.—Result of one transformer of a star connected primary and secondary group being cut out of circuit.

It is also worthy of note that the transformer which has one end tapped to the middle of the other transformer need not be designed for exactly $\frac{\sqrt{3}}{2}$ = 86.6 per cent. of the voltage; the normal voltage of one can be 90 per cent. of the other, without producing detrimental results.

Star *vs.* **Delta.** It is shown in Fig. 34 that should one of the three single-phase transformers be cut

out of star, or one of the leads joined to the neutral point be disconnected, there will exist only one voltage instead of three, across the three different phases.

This disadvantage is detrimental to three-phase working of the star arrangement, inasmuch as two phases of the three-phase system are disabled, leaving one phase which may be distorted to a very high degree.

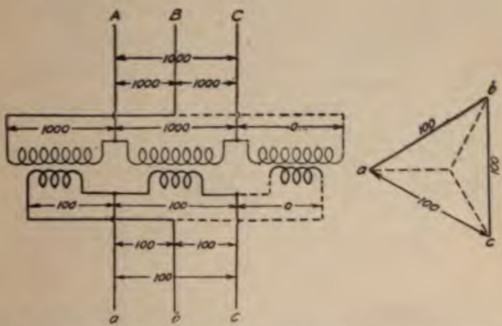


Fig. 35.—Result of a delta connected group of transformers with one transformer disconnected.

On the other hand, should one phase, or one transformer of a delta-connected group be disconnected from the remaining two, as shown in Fig. 35, there will exist the same voltage between the three different phases, and practically the same operating conditions.

The result obtained by cutting out of delta one transformer, is simply the introduction of open delta, which has a rating of a little over one-half

the total capacity; or more correctly, the rating of transformer capacity is

$$85 \text{ per cent.} \times 0.6666 = 0.5665$$

of three transformers of the same size connected in delta.

In the past it has frequently been urged against the use of three-phase transformers with interlinked magnetic circuits that if one or more wind-

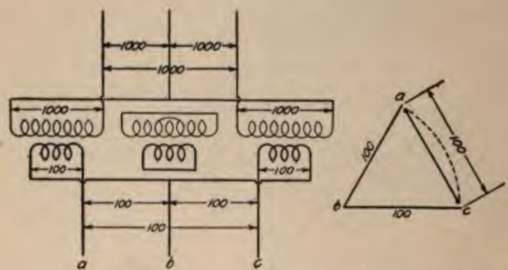


FIG. 36.—Result of operating a delta connected transformer with one winding disabled and short-circuited on itself.

ings become disabled by grounding, short-circuiting, or through any other defect, it is impossible to operate to any degree of satisfaction from the two undamaged windings of the other phases, as would be the case if a single-phase transformer were used in each phase of the polyphase system.

All that is necessary is to short-circuit the primary and secondary windings of the damaged transformer upon itself, as shown in Fig. 36. The

windings thus short-circuited will choke down the flux passed through the portion of the core surrounded by them, without producing in any portion of the winding a current greater than a small fraction of the current which normally exists at full load.

With one phase short-circuited on itself as mentioned above, the two remaining phases may be reconnected in open delta or in tee for transforming from three-phase to three-phase; or the windings may be connected in series or parallel for single-phase transformation.

CHAPTER V.

THREE-PHASE TRANSFORMER DIFFICULTIES.

In the operation of three-phase transmission systems many difficulties are encountered, and much is to be said regarding the relative merits of connections. Where the amount of power is great and the system extensive, the delta arrangement will generally be preferred on account of precluding the possibility of potential rises. The selection of delta or star system of transformation for long-distance transmission should be determined after a careful study of the conditions in each case.

In case of an accident to one unit of a three-phase group, the other units in circuit with it will immediately begin to establish current in the disabled one; and the increased load on the good units, due to their normal load plus the short-circuit current supplied to the damaged unit will, in all probability, interrupt the service.

Great developments in power transmissions of large kilowatt capacity over long distances are gradually taking the place of local generating plants supplying cities with electrical energy for varied industries. Rapid advance has created new conditions, necessitating radical departure from designs of recent date, some not yet put into

operation, and if so, they have not had sufficient time to demonstrate their worth at the design of maximum potential throughout the entire system.

From the point of view of good reputation, safety to life, and abnormal expense to electric power companies, it is of vital importance to obtain a correct perspective of all advantages and disadvantages, before making a final decision in favor of any system of long-distance transmission.

Most of the troubles which occur on transmission systems are put down to line surging, resonance, or some other unknown phenomenon on lines, and as a matter of fact the most of the troubles are in the transformers themselves, which are damaged and their phase relations twisted so as to produce in some instances many times the normal voltage.

The most disastrous troubles that can happen to a three-phase system are those of complex grounds and short-circuits. With a grounded neutral star system, a ground on any one phase is a short-circuit of the transformers, and the entire group becomes disabled.

The voltage between windings and the core is limited to 57.7 per cent. of that of the line, and the insulation between the windings and the core is likewise reduced in proportion. The voltage between mains and the ground is 57.7 per cent. of the line voltage, with either a delta or star connection, but the neutral point may move so as to increase the voltage with an ungrounded system.

If one circuit is grounded, the voltage between the other two circuits and the ground is increased, and may be as great as the full line e.m.f. Such unbalancing would cause unequal heating of the transformers and if a four-wire three-phase system of distribution were employed, would prove disastrous to the regulation of the voltage.

The examples cited in this chapter are understood

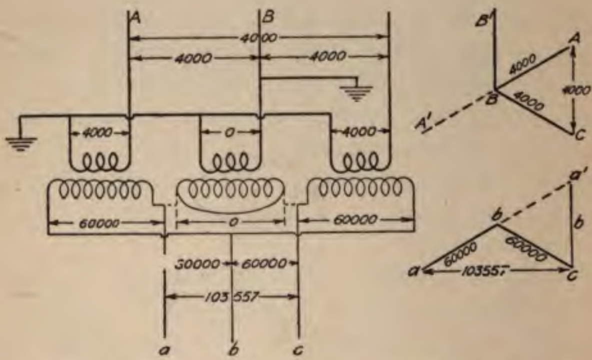


FIG. 37.—One transformer short-circuited and cut out of delta.

to have no other grounds than those on the lines and transformers, and the transformers are for 2,300 to 24,600 volts with delta-delta arrangement.

With a star-delta system as shown in Fig. 37, where a transformer is short-circuited and cut out of delta on the secondary, it is possible to obtain $\sqrt{3}$ times the potential of any one of the

transformers. In Fig. 37, $A\,B\,C$ represents the vector triangle of e.m.fs. on the primary with full line voltage or 4,000 volts, impressed on the transformers, which under normal conditions should be

$$4{,}000 \times \frac{1}{\sqrt{3}} = 2{,}300 \text{ volts.}$$

The phase relations are changed to 60 degrees, which convert the original star arrangement to an open delta; one phase is reversed, the resultant

FIG. 38.—Primary e.m.fs. and phase relations.

e.m.f. being the same as that across any two phases. See also vector diagram, Fig. 38.

As each transformer is only designed for 2,300 volts the e.m.f. across the secondary windings should be 34,600 volts, but in this case the voltages are 34,600 times $\sqrt{3}$ or 60,000 volts.

The secondary vector e.m.fs. are graphically represented to the right of Fig. 37. In order to bring the resultant vector secondary e.m.f., a and c, in its proper position the components must be drawn parallel with the primaries.

One secondary winding is short-circuited and

cut out of delta leaving an open-delta connection reversed in direction, its phase relations being changed from 60 to 120 degrees; increasing the voltage between a and c to

$$34{,}600 \times 1{,}732 \times 1{,}732 = 103{,}557 \text{ volts.}$$
$$\text{or } \sqrt{3} \times \sqrt{3} \times 34{,}600 = 103{,}577 \text{ volts.}$$

This is a very important point to bear in mind, especially when generators are tied directly to the system without fuses or any protecting devices.

The voltages impressed on the primary windings of Fig. 37 and 38 are:

A and B = 4,000 volts,
B and C = 4,000 volts,
A and C = 4,000 volts.

E.m.fs. between the primary neutral and any line, are:

A and A' = 4,000 volts,
which should be $4{,}000 \times 0.577$ = 2,300 volts;
B and B' = 0 volts,
which should be 2,300 volts;
C and C' = 4,000 volts,
which should be $4{,}000 \times 0.577$ = 2,300 volts.

The e.m.fs. between the secondary lines, are:

a and b = 60,000 volts,
which should be $60{,}000 \times 0.577$ = 34,600 volts;
b and c = 103,577 volts,
which should be $103{,}577 \div 2.99$ = 34,600 volts;
a and c = 60,000 volts,
which should be $50{,}000 \times 0.577$ = 34,600 volts.

The increases in e.m.f. across the secondary lines, are:

a and c = 173 per cent. above normal,
b and c = 300 per cent. above normal,
a and b = 173 per cent. above normal.

It is also found that where the neutral points of the primary and secondary windings are grounded, the opening of one or two of the three line circuits will cause currents through the ground. And a partial ground on a line circuit will partially short-circuit one transformer and cause current through the ground to the neutral.

The actual strain between high-tension and low-tension windings is equal to the high-tension voltage plus or minus the low-tension voltage, depending upon the arrangement and connection of the coils; but as the low-tension voltage is usually a small percentage of that of the high-tension, it is customary to assume that the strain between windings is equal to that of the high-tension voltage alone.

If the neutral points of the high-tension and low-tension windings are grounded, the iron core being also grounded, then as long as the circuits are balanced the voltage strains will be the same as with the windings ungrounded, and balanced; but in case of a ground on either high-tension or low-tension line, or in case of a connection between high-tension and low-tension windings, a portion of the windings will be short-circuited.

Assuming that all lines and transformers are in

good shape, that is to say, clear from grounds and short-circuits, it is possible to obtain any of following results shown in Figs. 39, 40, 41 and 42, by connecting the receiving ends of transmission lines to a wrong phase terminal receiving three-phase current from another source of supply, or by switching together groups of two or more transformers of the wrong phase relations.

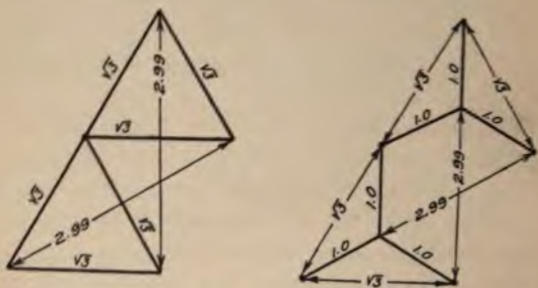


FIG. 39.—Resultant e.m.fs., and phase relations of improper delta-delta and star-star connected group of transformers.

Fig. 39 represents the result of a delta-delta and star-star combination thrown together at 120 degrees apart, both transmission lines receiving three-phase currents of the same potential, phase relations, and frequency.

The resultant voltage obtained in attempting to parallel two groups of three transformers either delta or star connected is $\sqrt{3}$ times the e.m.f. between any two line wires, or

Delta = 100 × 1,732 = 173.2 volts,
Star = (57.7 × 1,732 = 100) × (1,732) = 173.2 volts.

The combination shown in Fig. 40 represents four groups of three single-phase transformers

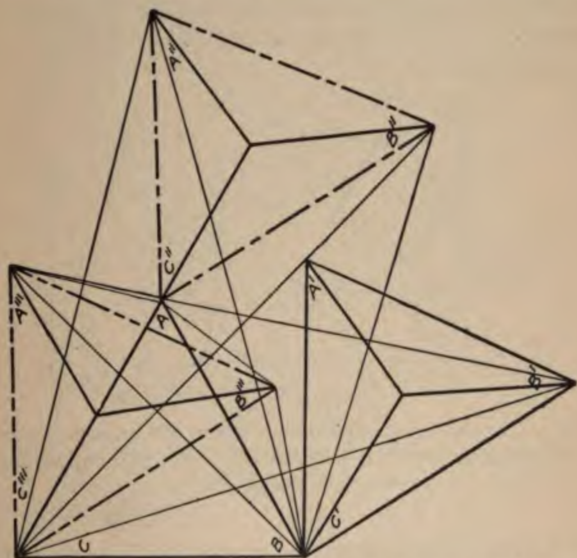
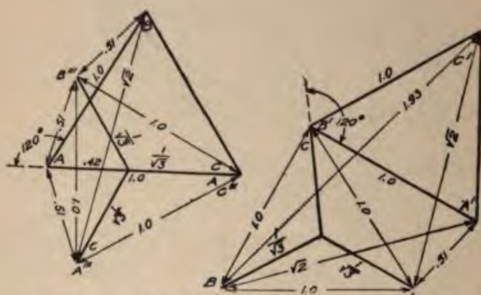


Fig. 40.—Representation of a complete combination of delta-delta and delta-star transformer group connections.

in each group connected to one set of busbars. Each group receives three-phase current from independent source of supply and is so tied-in on the primary and secondary busbars as to involve a partial short-circuit.

In common practice this combination is more often likely to happen on large distributing systems where all transformers in groups are tied together on primaries and secondaries. As will be noticed, any attempt to connect such a system with all primary windings and all secondary windings of each group in parallel will produce a short-circuit.



FIGS. 41 A and B.—Graphic illustration of e.m.fs. and phase displacement of two delta-delta to delta-star connected groups of transformers.

With a delta-star presupposed parallel operation it is impossible to change the magnetic field to correct the phase displacement which occurs, though it is possible in the case of generators which are necessary for permitting the 30 degrees electrical displacement to be corrected by a mechanical twisting of the phases with respect to their magnetic fields; but with transformers it is impossible.

The phase displacements show a star connection introduced in which the relative e.m.f. positions are changed by an angle 30 degrees. If, for example, we assume the line potential to be 60,000 volts, and we attempt to connect the groups as shown in diagram, the result will be voltages as high as 116,000.

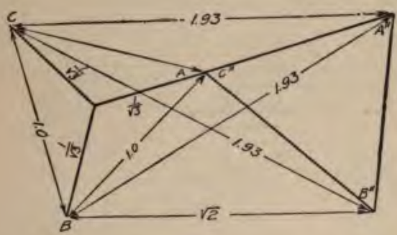


FIG. 42.—E.m.fs. and phase relation of a delta-delta to delta-star connected group of transformers.

The resultant e.m.fs. established by this experiment, are shown separately in Figs. 41 and 42. They are correctly:

B'' to B =	84,840 volts,	which should be =	0
B'' to C =	116,000 volts,	which should be =	60,000
A'' to C =	116,000 volts,	which should be =	60,000
A'' to B =	116,000 volts,	which should be =	60,000
A' to B =	84,840 volts,	which should be =	60,000
A' to C =	31,000 volts,	which should be =	60,000
C' to B =	116,000 volts,	which should be =	60,000
C' to C =	84,840 volts,	which should be =	60,000
B''' to B =	31,000 volts,	which should be =	0

B''' to A = 31,000 volts, which should be = 60 000
A''' to A = 31,000 volts, which should be = 0
A''' to B = 84,840 volts, which should be = 60,000

A fact not very well recognized, is the impossibility of paralleling the primaries and secondaries three-phase, except in the following combinations:

Delta-star group with a delta-star.
Star-star group with a star-star.

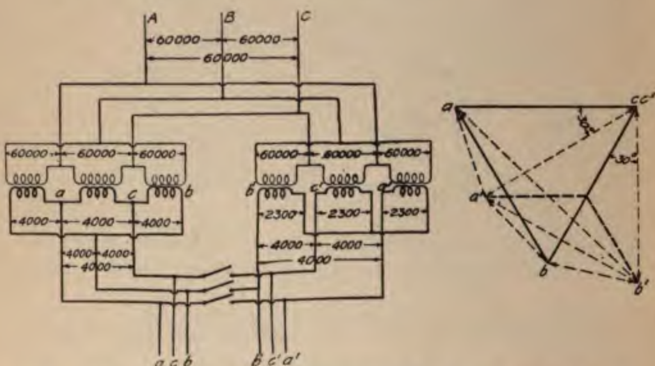


FIG. 43.—Practical representation of a delta-delta to delta-star connected group of transformers.

Delta-delta group with a delta-delta.
Star-delta group with a star-delta.
Delta-star group with a star-delta.
Star-star group with a delta-delta.

These delta-star combinations necessitate changing transformer ratios of primary and secondary turns, as:

Delta-star is a constant of $\sqrt{3}$ = 1.733 to 1.

Star-delta is a constant of $\frac{1}{\sqrt{3}} = 0.577$ to 1.

consequently, special ratios of secondary to primary turns are needed in delta-star or star-delta transformers, in order to produce standard transformation ratios.

Displacement of phase relations occur on the secondary when an attempt is made to tie-in a delta-delta with a delta-star; the delta-delta having a straight ratio and the delta-star a ratio of 1 to 0.577; or any of the following combinations:

Delta-star ratio $\frac{1}{\sqrt{3}}$ to 1, and star-star with ratio 1 to 1.

Delta-delta, ratio 1 to 1, with a star-star ratio $\frac{1}{\sqrt{3}}$ to 1.

Star-delta, ratio 1 to $\frac{1}{\sqrt{3}}$, and star-star with ratio 1 to 1.

The phase relations occupy a relative shifting position of 30 degrees on one group of transformers to that of the other. A more practical representation of the secondary voltages and phase relations of a delta-delta and delta-star is shown in Fig. 43.

CHAPTER VI.

THREE-PHASE TWO-PHASE SYSTEMS AND TRANSFORMATION.

With two or three single-phase transformers it is possible to have three-phase primaries with two-phase secondaries, or *vice versa*. For long-distance transmission of electric power the three-phase system is universally adopted because it requires less copper for the line than either the single-phase or the two-phase systems to transmit a given amount of power with a given line loss, and with a given line voltage. The two-phase system offers certain advantages over the three-phase system when applied to local distribution of electric power.

In Fig. 44 is shown the well known three-phase three-wire to two-phase four-wire transformation. Two transformers are all that is necessary in this arrangement, one of which has a 10 to 1 ratio and the other a 10 to 0.866, or 10 to $\frac{\sqrt{3}}{2}$.

One wire, b, of the 10 to 0.866-ratio transformer is connected to the middle point of the 10 to 1 ratio transformer, the ends of which are connected to two of the three-phase mains, a c; d, the end of the other transformer is connected to the remaining wire of the three-phase mains.

It is customary to employ standard transformers for the three-phase two-phase transformation, the main transformer having a ratio of 10 to 1, and the other transformer a ratio of 9 to 1.

By a combination of two transformers it is possible to change one polyphase system into any other polyphase system.

The transformation from a three-phase to a two-phase system may be effected by proportion-

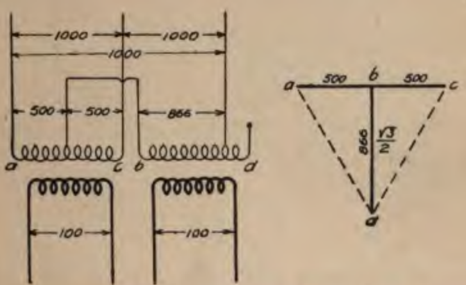


FIG. 44.—The ordinary three-phase two-phase connection.

ing the windings, as shown in Fig. 45. The three transformers are wound with a ratio of transformation of 10 to 1. The secondaries of two of the transformers have two taps each, giving 57.7 per cent. and full voltage, so that they serve as one phase of the two-phase transformation. The primary windings are connected in star.

The secondary windings are also connected in star. In Fig. 45, $b\ b'$ represents the secondary voltage from b to b' in one transformer. At an angle of

90 degrees to $b\,b'$ the line, $a\,a'$, represents in direction and magnitude the voltage, a to a', which is the resultant of the two remaining transformer e.m.fs., giving 57.7 per cent. of the full voltage. $57.7 \times \sqrt{3} = 100$. From the properties of the angles it follows that, at the terminals, $a\,a'$ and $b\,b'$, two equal voltages will exist, each differing from the other by 90 degrees, and giving rise to a two-phase current.

Another approximate and convenient method of

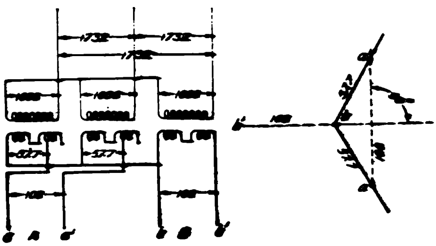


FIG. 45.—Three-phase star to two-phase four-wire secondary.

getting two-phase from three-phase, or the reverse, is shown in Fig. 46. At 1, 2 and 3, are the three primary coils of transformers connected to a three-phase circuit whose lines are 4, 5 and 6. At 1a, 2a and 3a are the corresponding secondary coils of said transformers.

The secondary coil, 3a, is tapped at about 86.6 per cent. of its length from one end, at about the point B, by a lead which serves as one leg of the two-phase circuits.

The secondary coil, $2a$, is tapped at the center point, A, by a lead, also forming one leg of the two-phase circuit.

The secondary coil, $1a$, is tapped at D, which is about 86.6 per cent. of its length from one end, by a lead, which serves also as a leg for the two-phase circuit.

By this arrangement it is possible to obtain both

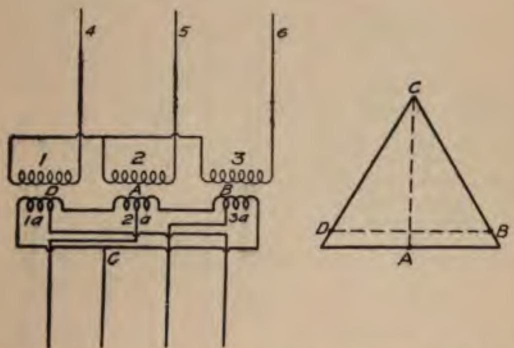


FIG. 46.—Three-phase delta to two-phase four-wire secondary.

two-phase as well as three-phase secondary currents.

Another method of getting two-phase from three-phase, or *vice versa*, consists in cutting one phase, say (Fig. 47) the middle transformer of the delta-connected group, in half, and arranging one-half to the left at b' c, and the other half to the right at b'' a.

The resultant of $a\ b'$ and $b'\ b$ is one side, or one phase of the two-phase transformation.

The resultant of $a\ b''$ and $b''\ c$, is the other phase of the two-phase transformation.

It is evident as shown in Fig. 47 that the two-phase relation is a trifle over 90 degrees; since the angle, $b\ b''\ x$ and $b\ b'\ x$, is 60 degrees, and the sine of 60 degrees is equal to $\frac{\sqrt{3}}{2} = 0.866$, the tangent of

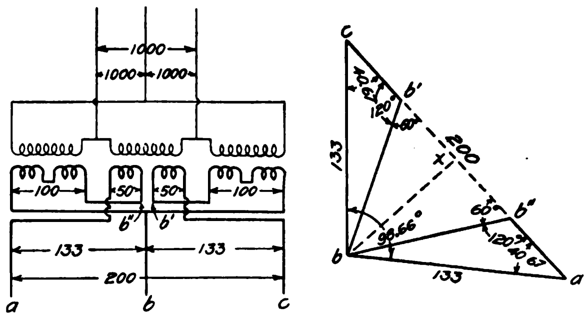


FIG. 47.—Three-phase delta to two-phase three-wire secondary.

the angles, $b\ c\ x$ and $b\ a\ x$, are likewise $\frac{\sqrt{3}}{2} = 0.866$

Therefore, the angle, $a\ b\ c$, must equal 90 degrees nearly.

The angle, $b\ c\ a$, whose tangent is 0.866 is an angle of 40.67 degrees; therefore,

$(b\ c\ x = 40.67) + (b\ a\ x = 40.67) + (a\ b\ c = 98.66) = 40.67 + 40.67 + 98.66 = 180$ degrees, nearly.

The approximate voltage obtained between *c b* and *b a* is 133 volts.

With two or more transformers it is possible to transform from three-phase to two distinct phase currents of three-phase and two-phase systems. In the arrangement shown in Fig. 48 only two transformers are used. The two primary windings are connected to the three-phase mains. One transformer is wound with a ratio of transforma-

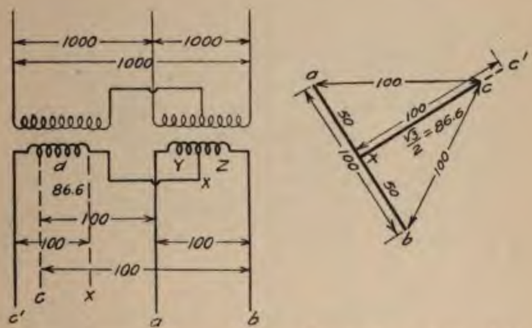


FIG. 48.—Three-phase tee to three-phase two-phase.

tion of 10 to 1. The other with a ratio of 0.866 to 1. The primary and secondary windings of this transformer is connected to the middle of the primary and secondary windings, respectfully, of the first.

a b represents the secondary voltage from *a* to *b* in one transformer. At right angles to *a b* the line, *x c′*, represents in direction and quantity, the voltage, *x* to *c′*, of the second transformer.

At the terminals, *a b c*, three equal voltages will exist, each differing from the other by 60 degrees, and giving rise to a three-phase current.

It also follows that, at the terminals *a b* and *x c′*, two equal voltages will exist, each differing from the other by 90 degrees, and giving rise to a two-phase current. As will be noted, the voltages obtained in the three-phase side are equal to those between any phase of the two-phase system.

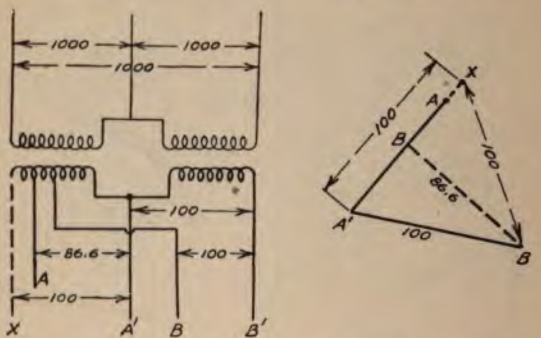


FIG. 49.—Three-phase open delta to three-phase two-phase

The arrangement in general is similar to that of the ordinary tee system.

Another combination somewhat similar to the above is shown in Fig. 49. The primary windings of the two transformers are connected in open-delta. The secondary windings are connected in such a manner as to give off two distinct phase currents; one kind differing in phase by 90 degrees, and the other by 120 degrees. From one secondary

winding two special taps of 50 per cent. and 86.6 per cent. are brought out to complete the circuits of three-phase and two-phase secondary. By this method of connection it is possible to obtain two-phase currents from $A\ A'$ and $B\ B'$, also three-phase currents from $x\ A'$, $A'\ B$, and $B\ x$, the two-phase e.m.fs. will be 86.6 per cent. of those of the three phase.

The method shown in Fig. 50 is a device patented

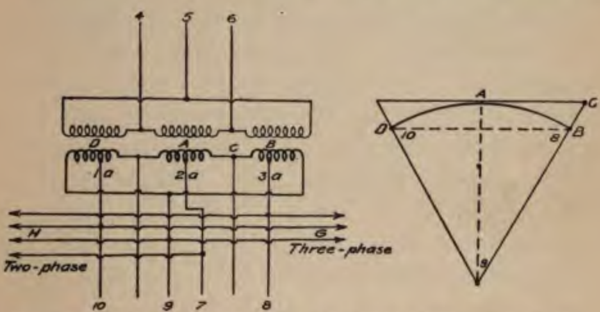


FIG. 50.—Three-phase delta to three-phase two-phase.

by the writer, and employed to operate both two-phase and three-phase electric translating devices, on one four-wire system of distribution; and to operate independent systems in parallel circuit on said four-wire system.

Three single-phase transformers are used. The primary windings are connected in delta, and the secondary windings are also connected in delta. A distribution line, 7, tapped at the middle of the secondary winding, $2a$; a distribution line, 8,

tapped at $\frac{\sqrt{3}}{2}$ per cent. of the length from one end of the winding, 3*a*; a distribution line, 9, tapped on the connection between the end windings, 2*a* and 3*a*; a distribution line, 10, tapped at $\frac{\sqrt{3}}{2}$ per cent. of the length from the end of winding 1*a*, and translating means connected on said distribution lines both for two- and three-phase on.

At 1*a*, 2*a* and 3*a* are the secondary windings of said transformers. The secondary winding, 1*a*, is tapped at *D*, which is about 86.6 per cent. of its length, by the line, 10; which serves also as a leg for both the two- and three-phase circuits. The secondary winding, 2*a*, is tapped at its central point *A*, by a line, 7; forming one leg of the two-phase circuit. The secondary winding, 3*a*, is tapped at approximately 86.6 per cent. of its length from one end, at about the point, *B*, by a line, 8, to serve as one leg of both the three- and two-phase circuits. *C* represents the point of a tap taken from the junction of two secondary windings which are shown connected in the series circuit, which serves as another leg for both two- and three-phase circuits.

The arrangement accomplishes the operating of synchronous and non-synchronous apparatus of two-phase and three-phase design without the aid of transformers or split-phase devices. The operation consists in generating three-phase alternating currents in the lines, 4, 5 and 6, transforming the

same into three-phase currents in the legs, 8, 9 and 10, and into two-phase currents in the legs, 7, 8, 9 and 10; and in operating translating devices at *G* and *H* in parallel with the two- and three-phase current circuits. The two-phase windings used on the motors must be independent as the inter-connected type of winding would not operate on this system.

It is possible to take three-phase currents from a three-phase system and transform them into a single-phase current; see Fig. 51. All that is

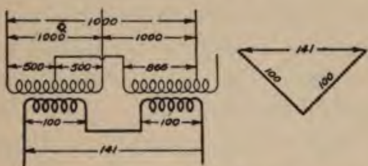


FIG. 51.—Three-phase to single-phase.

necessary is to arrange two transformers so that their connections are identical with the ordinary two-phase to three-phase transformation, the only difference being in the secondary, which has the two windings connected in series for supplying a single-phase circuit.

In the ordinary three-phase to two-phase transformation, the two components in each half of the winding differ in phase by 90 degrees. However, when the secondary circuits are connected in series, these two component currents are of one phase.

CHAPTER VII.

SIX-PHASE TRANSFORMATION AND OPERATION.

In transforming from three-phase to six-phase there are four different ways of connecting the secondaries of the transformers: namely, diametrical—with or without the fixed neutral point; double star; double delta; and double tee. In the first three cases the primaries may be connected either star or delta, according to the voltage that each winding will stand, or to obtain a required secondary voltage. In the last case, the primary windings are connected in tee.

For the diametrical connection three single-phase transformers may be used with one central tap from each transformer secondary winding, or there may be six secondary coils. For the double-star or double-delta connection two independent secondary coils are required for each transformer; the second set are all reversed, then connected in a similar manner to the first set. Hence, the phase displacement is shifted 180 degrees.

For the double-tee connection two single-phase transformers are required, one of which has a 10 to 1 ratio and the other a 10 to 0.866, or 10 to $\frac{\sqrt{3}}{2}$ ratio.

There are two secondary coils giving 10 to 1 ratios, and two giving 10 to 0.866 ratios.

In six-phase circuits there are coils with phase displacements of sixty degrees; each coil must move through 180 electrical degrees from the position where the current begins in one direction, before the current begins to reverse. Hence, for the double star, diametrical, double delta and double-tee connections if the ends of the trans-

FIG. 52.—Six-phase diametrical e.m.fs. and phase relation.

former coils are reversed, the phase displacement of the e.m.f. is in effect shifted 180 electrical degrees.

Take for instance the e.m.fs., $a\,a'$, $b\,b'$ and $c\,c'$, as graphically explained in Figs. 52 and 53, for a diametrical connection they are equal to $2\,a\,x$, $2\,b\,x$, $2\,c\,x$, etc.

For double-star connection:

$a\,b'$, $b'\,c$, $c\,a$, etc., is $\sqrt{3}$ times $x\,a$, $x\,b'$, $x\,c$, etc.

For double-delta connection:

$x\,a$, $x\,b'$, $x\,c$, etc., is $\frac{1}{\sqrt{3}} = 0.577$ per cent. of $a\,b'$, $b'\,c$, $c\,a$, etc.

For double-tee connection:

$a\,b'$, $b'\,c$, $c\,a$, etc., is 13.3 per cent. more than $a'\,y$, or $a\,z$.

The general statement of relationship between

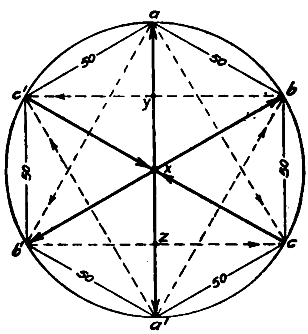


FIG. 53.—Six-phase e.m.fs. graphically represented.

e.m.fs. in Fig. 53 shows that if the value of $a\,a'$, etc., is represented by the diameter of a circle, then the values of $a'\,b$, etc., is represented by a 120-degree chord, and the value of $a\,b$, etc., is represented by a 60-degree chord of the same circle.

If the voltage between, $a\,b$, etc., is not required, only three secondary coils are needed; but if this voltage should be required, then six secondary coils are needed, or three coils with a center tap

like that shown in Fig. 54. The diametrical connection of transformer secondaries as represented in Fig. 54 is the most commonly used of any three-phase to six-phase transformations. One secondary coil on each step-down transformer is all that is necessary; whereas the double-star, double-delta and double-tee connections require two secondary coils, and therefore four secondary wires for each transformer.

The two secondary wires from each transformer

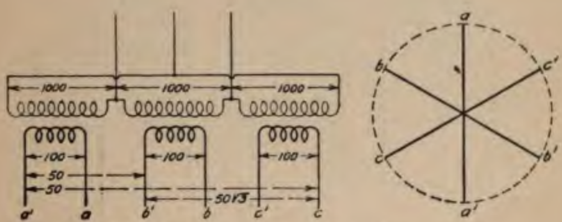


FIG. 54.—Six-phase diametrical connection.

are connected to the armature winding of a rotary converter at points 180 degrees apart—such as shown at $a\,a'$, $b\,b'$, $c\,c'$; therefore, arrangements for the diametrical connection are much simpler than any of the others.

A part of the three-coil secondary diametrical connection may be used for induction-motor service to start the rotary converter, and when sufficient speed is obtained the motor may be cut out of service. The arrangement is shown in Fig. 55. By means of this connection, which is made

through the introduction of a five-pole switch, a three-phase e.m.f. may be obtained, giving a value equal to half the e.m.f. of each secondary winding times $\sqrt{3}$. That is to say, if half the e.m.f. of each secondary winding is equal to 50 volts, then assuming the switch to be closed, we obtain $50\times\sqrt{3}=86.6$ volts.

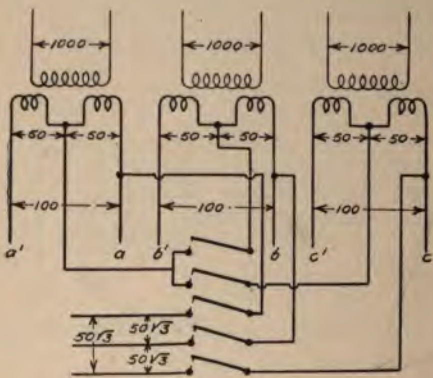


FIG. 55.—Six-phase diametrical connection with five-point switch used in connection with motor for starting synchronous converters.

Similar ends of the three windings are connected to three points on one side of the five-pole switch. The three wires on the other side of the switch are led off to the three-phase motor service. The two remaining points of the switch receive three wires from the neutral points of the three secondary windings. Connections are so made that

when the switch is closed a star-connection is obtained.

With the double-star arrangement of secondary windings, shown in Fig. 56, a rotary converter may be connected to a given three of the six secondary coils, or one rotary may be connected to the six secondary coils. The disadvantage of star connection is that in case one transformer is burned out, it is not possible to continue running.

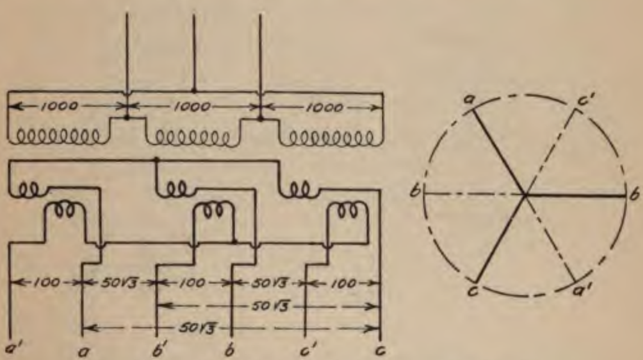


FIG. 56.—Six-phase double-star connection.

An arrangement for six-phase transformation is shown in Fig. 57, which differs from that of Fig. 56 in that the middle point of each transformer winding is tied together to form a neutral point for the double star combination.

It is common practice to connect the neutral wire of the three-wire, direct-current system to the neutral point of the star connection.

It may be seen that the similar ends of the two coils of the same transformer or similar ends of any two coils bearing the same relation to a certain primary coil are at any instant of the same polarity.

The double-delta secondary arrangement should preferably be connected delta on the primary, as it permits the system to be operated with only two transformers, in case one should be cut out of circuit.

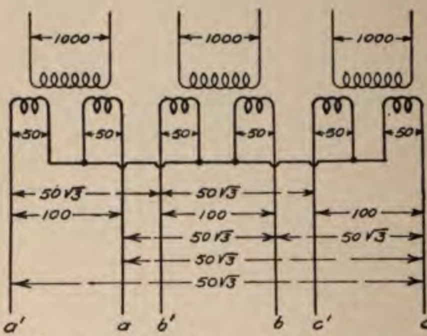


FIG. 57.—Six-phase double-star with one neutral point for the six secondary windings.

One set of the three secondary coils is connected in delta in the ordinary way, but the leads from the second set are reversed and then connected in a similar manner.

It may be seen from Fig. 58 that two distinct delta connections are made, and in case it is desired to connect the six leads, *a b c a′ b′ c′*, to a six-phase rotary converter it is necessary that each be connected to the proper rings.

The double-tee connection requires only two transformers, and so far as concerns the cost of the equipment and the efficiency in operation two tee-connected transformers are preferable to the delta or star connections. This connection can be used to transform two-phase to six-phase, and from three-phase to six-phase.

It is worthy of note that the transformer with

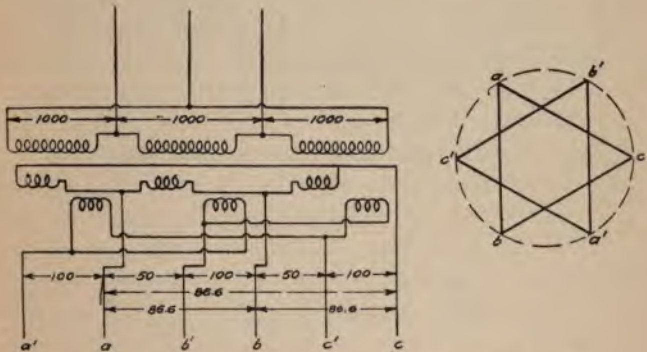


FIG. 58.—Six-phase double-delta combination.

the 86.6 per cent. winding need not necessarily be designed for exactly 86.6 per cent. of the e.m.f. of the other transformer; the normal voltage of one can be 90 per cent. of the other, without producing detrimental results.

Fig. 59 represents the tee-connection for transforming from three-phase to six-phase e.m.fs.

With reference to its ability to transform six-phase e.m.fs. and maintain balanced phase rela-

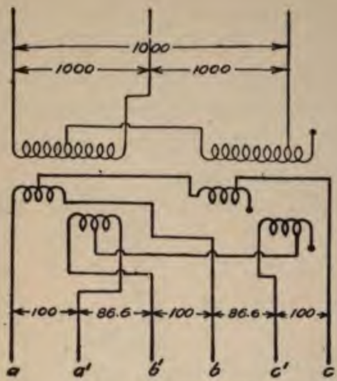


FIG. 59.—Six-phase tee connection.

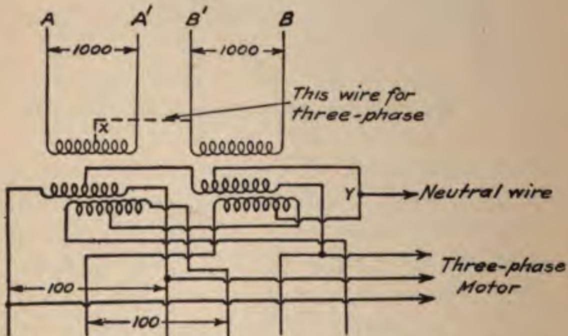


FIG. 60.—Six-phase from three-phase or two-phase.

tions, the tee-connection is much better than either the delta or star connections.

Another interesting method of transforming from three-phase or two-phase to six-phase is shown in Fig. 60. The two transformers bear the ratio of 10 to 1 and 10 to 0.866, as explained in the previous example. For a two-phase primary supply, $A\ A'$ is tapped on one phase, and $B\ B'$ is tapped on the other; the line, x, being cut loose. For a three-phase primary supply the lines, A, A', and B, are connected to the three-phase mains. The secondary connections in both cases remaining the same.

If a neutral wire is required as in the case of the three-wire, direct-current system, it may be taken from the point, y. For running a blower motor, or to furnish current for running the rotary converter up to synchronous speed by an induction motor mounted on the same shaft, any one of the two secondary tee-connections may be used. The three-phase e.m.f. obtained would have a value equal to the full secondary voltage used for the rotary converter.

CHAPTER VIII.

METHODS OF COOLING TRANSFORMERS.

Small transformers do not require special cooling devices since they have large radiating surface compared with their losses. Large transformers will not keep cool by natural radiation; some special cooling devices must be provided.

The various cooling methods are:

Self-cooling dry transformers.

Self-cooling oil-filled transformers.

Transformers cooled by forced current of air.

Transformers cooled by forced current of water.

Transformers cooled by forced current of oil.

Transformers cooled by combination of above means.

Self-cooling dry transformer.—Transformers of this kind are usually of small output, and do not require any special means of cooling, the natural radiation being depended upon for cooling.

Self-cooling oil transformers.—This arrangement is employed for at least 60 per cent. of transformers in use, the core and coils being immersed in oil. The two advantages gained by immersing these transformers in oil, are: Insulation punctures are immediately repaired by the inflow of oil, and the temperature is reduced by offering means of escape for the heat.

Many manufacturers depend upon the high insulating qualities of the oil itself, and, therefore, introduce less insulating material such as cambric and mica, etc. On the other hand if oil is punctured it will close in again, unless the puncture be the result of a short-circuit in the transformer, in which case an explosion is liable to occur, or a fire to be started. In this way many electric plants have been destroyed.

For the purpose of obtaining the necessary radiating surface, tanks of the large self-cooled transformers of many manufacturers are made of thin corrugated steel or cast iron. The thin corrugated steel metal tanks are not sufficiently strong to be safely handled in transportation with the transformers in them. A slight blow is sufficient to cause the oil to leak at the soldered seams between the different sheets of thin steel, or at the joints between the sides. The cast-iron case is unquestionably the best, and the most suitable for oil transformers; the great strength and stability of cast-iron cases insure the safe transportation of the transformer.

In the design of oil-insulated transformers, interior ventilation is provided by oil passages or ventilating ducts, between the coils, and in the iron. These secure an even distribution of heat and a uniformity of temperature throughout the transformer, results which can be secured only by a free internal circulation of oil.

Without good oil circulation, transformers of

large size may reach an internal temperature greatly in excess of that of the external surface in contact with the oil, and in poorly designed transformers this may lead to the speedy destruction of the insulation of the coils.

The number and size of the oil passages, or ventilating ducts are planned to keep all parts of the transformer thoroughly cooled. Such ducts necessarily use much available space and make a transformer of given efficiency more expensive than if the space could be completely filled with copper or iron. Experience with oil-insulated transformers of large size and high voltage has shown that oil increases the life of the insulation, in addition to acting as a cooling medium, and adds materially to the capability of the transformer to resist lightning discharges.

The amount of heat developed in a transformer depends upon its load and its efficiency. In a 500-kw. transformer of 98.5 per cent. efficiency there is a loss at full load of 7.5 kw. Since this loss appears as heat, it must be disposed of in some way or the temperature will rise until it becomes dangerously high.

Transformers cooled by forced current of air.—This type of transformer is commonly called the "air blast," and may be wound for any desired voltage not exceeding 40,000.

The method of cooling air-blast transformers is by a forced blast of air furnished by a blower. The blower may deliver air directly into a chamber

over which the transformer is located, or if it is more convenient, the blower may be located at a distance from the transformer, feeding into a conduit which leads to the air chamber. The blower is usually direct connected to an induction motor, though it may be driven by other means. One blower generally supplies a number of transformers in the same station, and the transformers are usually spaced above an air chamber, in which a pressure is maintained slightly above that of the surrounding air. The air for cooling the iron passes from the lower housing selected to suit the transformer capacity. When the efficiency of an air-blast transformer is known, an approximate estimate of the amount of air required can be made by allowing 150 cubic feet of air per minute for each kilowatt lost. For the most satisfactory operation, the velocity of the air in the chamber should be as low as possible, and should never exceed 500 feet per minute. That is, the cross-section of the chamber in square feet should at least be equal to the number representing the total volume of air required per minute by the transformer, divided by 500. The power required to drive the blower for furnishing air to the transformers is so small as to be practically negligible, amounting in most cases to only a fraction of one per cent. of the capacity of the transformers.

The three-phase, air-blast transformer, when delta connected, has the same advantage as three single-phase transformers of the same total rating

that is, by disconnecting and short-circuiting both windings of a defective phase, the transformer can be operated temporarily at two-thirds, or thereabouts, of the total capacity from the two remaining windings.

The insulation of air-blast transformers must be impervious to moisture, and must have superior strength and durability. It must also permit the ready discharge of the heat generated in the windings, as otherwise the transformer temperature may reach a value high enough to endanger the life of the insulation. In building such a moisture-proof insulation, the coils are dried at a temperature above the boiling point of water, by a vacuum process which thoroughly removes all moisture. After a treatment with a special insulating material, they are placed in drying ovens, where the insulating coating becomes hard and strong. Then the coils are taped with an overlapped covering of linen and again treated and dried, there being several repetitions of the process, depending on the voltage of the transformer. The insulating materials are so uniformly applied and the varnish so carefully compounded that the completed insulation on the coils is able to withstand potentials two or three times greater than the same thickness of the best insulating oil.

Transformers cooled by forced current of water.—This type of transformer is usually called "oil-insulated, water-cooled."

Inside the cast-iron tank and extending below

the surface of the oil, are coils of seamless brass tubing through which the cooling water circulates. These coils are furnished with valves for regulating the flow of water, and the proper adjustment having once been made, the transformer will run indefinitely with practically no attention. Another method of cooling is by drawing off the oil, cooling it, and pumping it back, the operation being continuous. In the design of oil-insulated, water-cooled transformers, interior ventilation is provided by oil passages between the coils, and in the iron. These secure an even distribution of heat and a uniformity of temperature throughout the transformer. Without good oil circulation, transformers of large size may reach an internal temperature greatly in excess of that of the external surface in contact with the oil. As a means of securing the best regulation, oil insulation is of immense advantage inasmuch as it permits close spacing of the primary and secondary windings. It effects great economy of space, and its fluidity and freedom from deterioration greatly assists in solving the difficult problems of transformer insulation. Its good qualities come into play with remarkable advantage in building high-potential transformers.

Water-cooling coils are made of seamless tubing capable of withstanding a pressure of from 150 to 250 pounds per square inch.

Transformers cooled by a combination method.— Transformers cooled by this method require the

service of a pump for circulating the oil. It being forced upwards through spaces left around and between the coils, overflows at the top, and passes down over the outside of the iron laminations. With such a scheme transformers can be built of much larger capacities than the largest existing water-cooled transformers of the ordinary type, without such increase in size as to show prohibitive cost and to necessitate transportation of the transformers in parts for erection at the place of installation. The forced oil allows the circulation of the oil to be increased to any extent, thereby producing a rapid and positive circulation which greatly increases the cooling efficiency of the oil. Moreover, this method of oil circulation ensures such uniform and positive cooling that much higher indicated temperatures may safely be permitted in transformers operating at moderate overloads.

With ample capacity provided in oil- and water-circulating pumps, the transformer can without danger be called upon to carry extreme overloads under emergency conditions. Transformers of the forced-oil type have recently been built for a normal capacity of 7,500 kilowatts, and actually capable of carrying 10,000 kilowatts continuously at a safe temperature.

CHAPTER IX.

AUTO TRANSFORMERS.

The ordinary auto-transformer is a transformer having but one winding. The primary voltage is usually applied across the total winding, or in other words, across the total number of turns, and the secondary circuit is connected between two taps taken off from the same winding, the voltage ratio being equal to the ratio of numbers of turns.

The auto-transformer shown in Fig. 61 has two taps brought out at *a* and *b*. Thus the whole or part of the winding may be used to raise the voltage or lower the voltage by simply changing the connections.

For example, the primary *a b*, is wound for 1000 volts, *a c* and *b d* each being wound for 50 volts. As will be seen, by taking a tap out from *a* and *d*, the secondary gives $1{,}000+50 = 1{,}050$ volts. And by moving to the far end of the winding, *a*, the voltage may be raised from $1{,}050+50=1{,}100$ volts. In order to obtain 550 volts all that is necessary is to bring two leads out from *x* and *d*, or *x* and *c*; the secondary then gives $1{,}050 - 500 = 550$ volts.

For pressure regulation auto-transformers are very convenient, being used to some extent for regulating the voltage of transmission lines. They

are also used for starting induction motors; and lately they have been used for single-phase railway service.

For series incandescent systems a transformer similar to that shown in Fig. 61 may be used. A portion of the winding, *a b*, is common to both primary and secondary. The secondary voltage, *c d*, is greater than the primary, *a b*, by the voltage

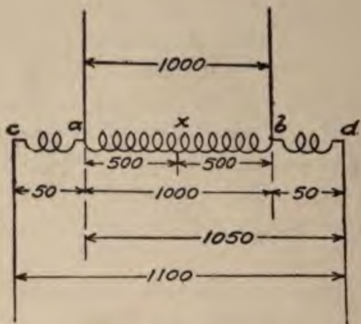


Fig. 61.—Step-up auto-transformer.

of the winding, *b d* and *c a*. The voltage, *b d* or *c a*, is thus added to the primary to form the secondary voltage of the circuit.

By reversing the connections of the winding, *b d* and *c a*, however, it may be made to subtract its voltage from the primary, *a b*; in which case the secondary voltage becomes less than the initial primary voltage; (Fig. 62). Further, by bringing a number of leads from parts of the winding, *b d*

or *c a*, the secondary voltage may be increased or decreased by successive steps as the different leads are connected to the secondary circuit. For a given transformation of energy, an auto-transformer may be considerably smaller than an ordinary transformer, and consequently its losses will be less and the efficiency higher. The amount of power delivered to the service mains at an increased voltage is very much greater than the power actually transformed from the primary to the secondary of the transformer. In fact, the power actually transformed is equal to the increase of voltage multiplied by the total current delivered; and the output, or actual rating of the transformer is based upon the power transformed.

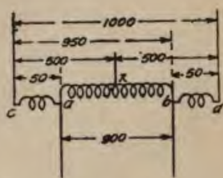


FIG. 62.—Step-down auto-transformer.

Example.—The voltage of a long-distance transmission line is to be raised from 40,000 to 45,000 volts, and the maximum current to be handled is 750 amperes. What is the rating of auto-transformer required for this service? and what will be the actual power delivered over the line?

The actual rating of the auto-transformer will be,

$$5{,}000 \times 750 = 3{,}750 \text{ kilowatts.}$$

The total power delivered to the line will be,

$$45{,}000 \times 750 = 33{,}750 \text{ kilowatts.}$$

In Fig. 62 the secondary voltage is smaller than

the primary. The voltage, *b d* and *c a*, are thus subtracted from the primary to form the secondary voltage of the circuit. The auto-transformer may thus act as a step-up or step-down transformer.

The action of an auto-transformer is similar to that of the ordinary transformer, the essential difference between the two lies in the fact that in the transformer the primary and secondary windings are separate and insulated from each other, while in the auto-transformer a portion of the winding is common to both primary and secondary. The primary and secondary currents in both types of transformers are in the opposite direction to each other, and thus in an auto-transformer a portion of the winding carries only the difference between the primary and secondary currents.

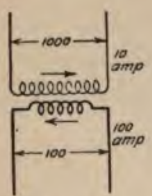


FIG. 63.—Standard commercial transformer connection.

In the foregoing explanation on auto-transformation the ordinary transformer will be used instead of the auto-transformer. This method of transformation is a very difficult subject to explain theoretically, since there are many different ways in which the ordinary transformer may be used.

There are shown in Fig's. 63, 64 and 65, three different ways of connecting the ordinary single-phase transformer. In this case it is assumed that the ratio of transformation is as 10 to 1,.and the rating 10 kw. at 1,000 to 100 volts.

It is very interesting to note the increased output, decreased losses, and better regulation, etc., attained by simply connecting the transformer in different ways.

Fig. 63 represents the ordinary transformation with the primary and secondary windings separated and insulated from each other. Neglecting

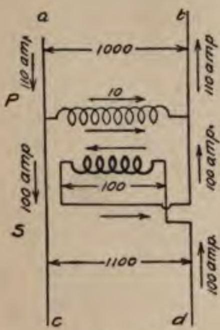


FIG. 64.—Standard transformer used as auto-transformer for stepping up the voltage.

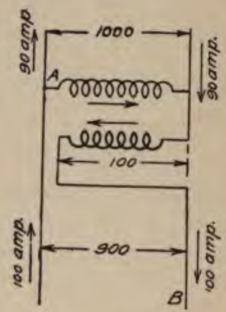


FIG. 65.—Ordinary transformer used as step-down auto-transformer.

all losses, in round figures the transformation would be 1,000 volts at 10 amperes = 10 kilowatts, to a secondary output of 100 volts at 100 amperes = 10 kilowatts.

In Fig. 64, *a* and *b*, are the primary mains, between which a voltage of 1,000 is impressed; *c* and *d* are the secondary mains, to which it is desired to deliver a current of 100 amperes at 1,100

volts. The currents in the primary and secondary of any transformer are always in opposition, or in other words, in opposite direction, inasmuch as they balance each others magnetizing action. Therefore, the 100 volts generated in the secondary winding will help to establish current in the secondary mains; in which case the generated voltage is added to the secondary supply, which is equivalent to 1,100 volts.

Assuming that the 100 amperes through the secondary in the same direction as the generated e.m.f., there are 10 amperes through the primary winding in opposition to the generated, or counter e.m.f. of 1000 volts. Therefore, the primary winding receives 10,000 watts from the supply mains, while power is transformed to the secondary by ordinary transformation, whence it is given out in raising the e.m.f. to the secondary service mains.

The total power delivered to the secondary service mains, *c d*, is evidently $100 \times 1{,}100 = 110$ kilowatts; but as a matter of fact we are only using a 10-kw. transformer. However, such is the actual case obtained above, which means that we have a total kilowatt capacity delivered to the service mains aggregating 110 kw.

Another very interesting arrangement of auto-transformation by using an ordinary single-phase transformer is shown in Fig. 65. In this case the e.m.f. generated in the secondary is subtracted from the primary voltage, in which case the secondary service voltage is only 900 volts.

Assume as in Fig. 63, that 100 amperes exists in the secondary winding in a direction opposite to the 100 volts of generated e.m.f. so that there are 10 amperes through the primary winding in the same direction as the generated e.m.f. of 100 volts. The 100 volts which is subtracted from the line voltage generates 1000 volts in the primary and supplies 10 amperes to the load.

The total power delivered to the secondary service mains, *c d*, is evidently $100 \times 900 = 90{,}000$ watts, which means that a total capacity of 90 kilowatts is delivered to the secondary service mains from a normally loaded 10-kw. transformer.

As is well known, there is a serious objection to auto-transformation by this arrangement, inasmuch as the secondary winding is connected directly to the primary, and conditions may arise from a ground on the primary circuit that will make the secondary dangerous to any person who happens to touch the secondary receiving circuit.

For instance: A ground on primary wire *A*, Fig. 65, and a person accidentally coming in contact with secondary wire *B*. The person will be subject to a full primary voltage of

$$1{,}000 - 100 = 900 \text{ volts.}$$

Two-phase, four-wire, auto-transformation as shown in Fig. 66, where the secondary winding is made to assist the primary, may be considered as two ordinary single-phase circuits. The ratio of transformation in this case is 10 to 1, therefore

we obtain by the connection as shown, a secondary voltage of 1,100.

By reversing the secondary connection it is possible for us to get $1{,}000 - 100 = 900$ volts.

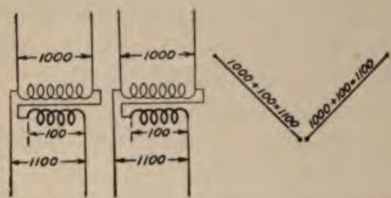


FIG. 66.—Two-phase auto-transformation.

If we should take one end of the secondary winding and connect it as shown in Fig. 67 we would obtain 50 per cent. of the primary voltage plus 100, which is the total secondary voltage. Then assum-

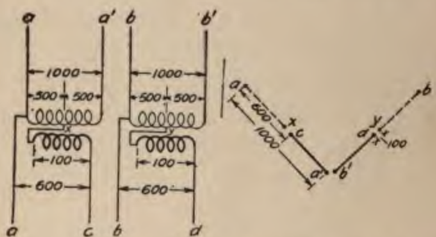


FIG. 67.—Two-phase four-wire auto-transformation.

ing the primary and secondary to have a four-wire, that is to say, two independent single-phase systems, we would have a secondary voltage of 500 plus $100 = 600$ volts. The points, x and y, are

taps brought out from the middle points of the windings.

Another two-phase auto-transformation is represented in Fig. 68. Both primary and secondary

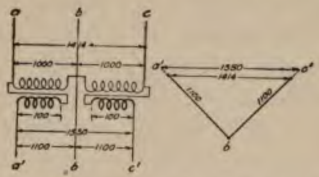


FIG. 68.—Two-phase three-wire auto-transformation.

are connected to a three-wire system from which we obtain a secondary voltage of 1,100 between a' b and b c', and 1,550 volts between a' and c', or

$$1{,}100\times 1.41 = 1{,}550 \text{ volts.}$$

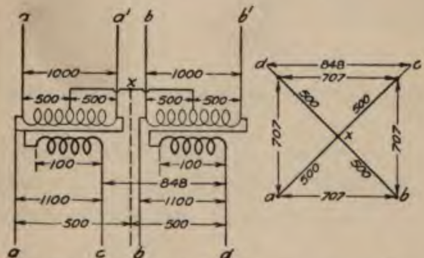


FIG. 69.—Two-phase five-wire auto-transformation.

A very interesting combination giving a five-wire, two-phase transformation is shown in Fig. 69. From this arrangement it is seen that quite a number of different voltages and phase relations can be

obtained, and by simply shifting the connection at x we increase and decrease the resultant voltages.

At $a\,x\,d$ and $c\,x\,d$ the respective phases that constitute the four-phase relation have been changed from 45 degrees to a slightly higher value, the voltage increasing in proportion to the increase of phase difference.

The three-phase arrangement shown in Fig. 70 is a method of auto-transformation by which we are enabled to supply approximately 1040 volts to

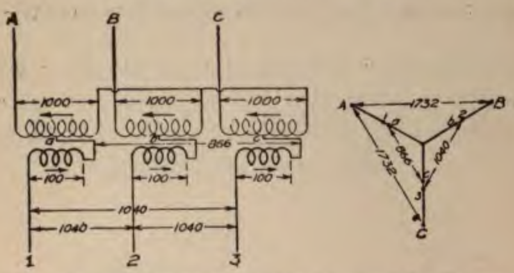


FIG. 70.—Three-phase star auto-transformation.

the secondary mains, 1, 2 and 3, from a 1,732-volt pirmary source of supply, using three transformers with a ratio of 10 to 1, or = 1,000 to 100 volts.

Between points $a\,b$, $b\,c$, $a\,c$, we obtain

$$500 \times \sqrt{3} = 866 \text{ volts.}$$

Between points 1 2, 2 3, and 1 3, there exists approximately

$$500 + 100 \times \sqrt{3} = 1{,}040 \text{ volts.}$$

The three-phase delta connection shown in Fig. 71, with its three secondary windings left open-circuited, may be used where a three-phase 500-volt motor is installed. The secondary windings, if required, may be used at the same time for lighting or power. To obtain a 100-volt lighting service it will be necessary to connect the secondary windings in delta, running a three-wire distribution to the source of supply, *a b c*. This

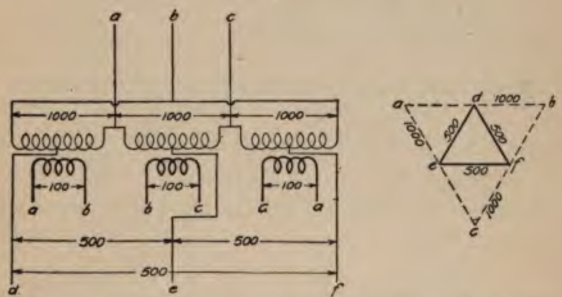


FIG. 71.—Three-phase auto-transformation with secondaries open circuited.

method of connecting transformers is often found useful in places where transformers of correct ratio are not obtainable.

The combination shown in Fig. 72 has its secondary windings connected in circuit with the primary windings. Like Fig. 71, a tap is brought out from the middle of each winding; but instead of leading out to the secondary distribution, it is connected to one end of the secondary winding as shown at 1,

2 and 3; the result of which represents a phase displacement as shown in the vector diagram.

Using the same transformers as in the previous

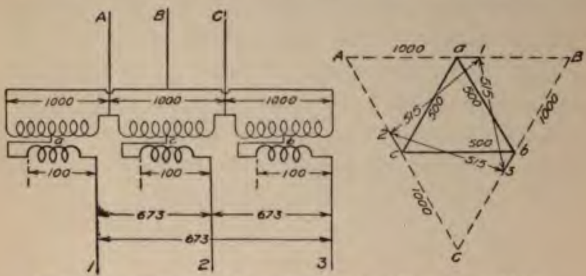


FIG. 72.—Three-phase delta auto-transformation.

examples, connecting $A\ B\ C$ to a $500 \times \sqrt{3} = 866$ volt supply (Fig. 73), it is possible for us to obtain a number of different voltages for the secondary

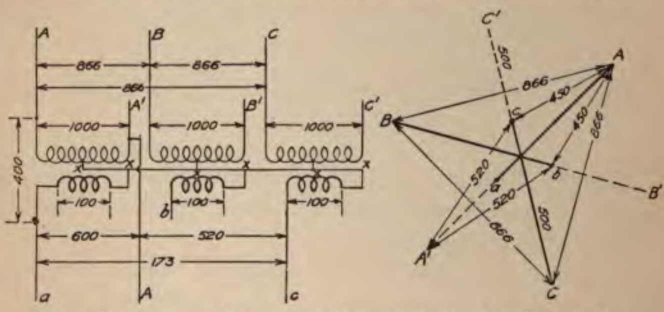


FIG. 73.—Three-phase double-star auto-transformation.

distribution, such as three at 1,000, three at 600, three at 520, six at 500, three at 173, and three at 100 volts, respectively (Fig. 73.) According to

the ratio of transformation applied at the secondary distribution it is understood that the kilowatt capacity of the transformers will vary.

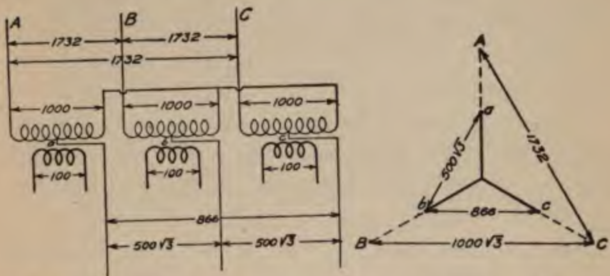


FIG. 74.—Three-phase star auto-transformation with secondaries open circuited.

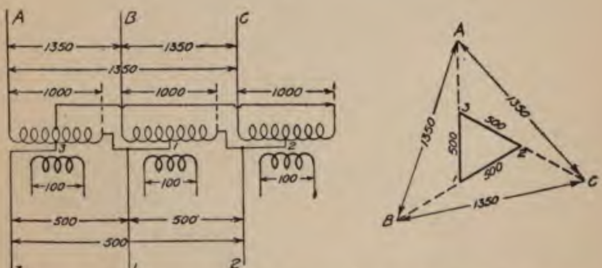


FIG. 75.—Three-phase auto-transformation using primary windings only.

Another three-phase combination is shown in Fig. 74, where it is shown that the primary windings are connected in star, and the three leads, *A B C* are connected to a 1,732-volt supply. From

the middle of each primary winding a tap is brought out at *a b* and *c*.

The secondary voltage across *a b*, *b c* and *a c* is $500 \times \sqrt{3} = 866$ volts. The 100-volt secondary winding may be used for power and lighting, single or polyphase, depending upon the size and design of the transformer.

Fig. 75 represents a three-phase transformation, using only the primary windings. One end of each primary winding is connected to the middle point of another primary winding. Three-phase, 1,350 volts, impressed on *A B C* will give 500 volts on 1–2, 2–3, and 1–3.

CHAPTER X.

CONSTANT-CURRENT TRANSFORMERS AND OPERATION.

For operating arc- and incandescent lighting systems from constant-potential, alternating-current mains, the constant-current transformer is frequently used. It is designed to take a nearly constant current at varying angles of lag from constant-potential circuits, and to deliver a constant current from its secondary winding to a receiving circuit of variable resistance. Thus the transformer automatically delivers a constant current from its secondary when a constant potential is impressed on its primary winding.

For the majority of series incandescent systems the constant-current transformer will be found lower in initial cost and more reliable in service than the reactive coil method, as it combines in one element the advantages of a regulating device and an insulating transformer.

The transformer consists in a core of the double magnetic type with three vertical limbs and two flat coils enclosing the central limb. The lower coil, which is fixed, is the primary, while the upper one, or secondary, is carried on a balanced suspension, and is free to move along the central limb of the core.

The repulsion between the fixed and moving

windings of the system for a given position is directly proportional to the current in the windings.

For series enclosed, arc-lighting on alternating-current circuits the constant-current transformer is universally used. It consists of a movable secondary and fixed primary windings, surrounded

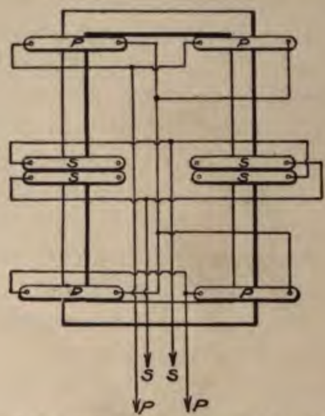


FIG. 76.—Type of constant-current transformer for arc lighting systems.

by a laminated iron core. This core and the yokes at the top, bottom and sides, form a double magnetic circuit, as shown in Fig. 76.

The magnetic flux which passes through the primary winding, flows partly through the secondary winding. The secondary winding is made movable and partly counterbalanced by a weight so that an increase in the current causes the second-

ary to be pushed further away from the primary. The weight is so adjusted as to sustain the coil against the leakage flux, and simply by changing the amount of counterweight the transformer can be adjusted to maintain any desired current.

In small transformers, which have but one movable coil, the counterweight equals the weight of the coil less the electrical repulsion, and a reduction in the counterweight will produce an increase in the current. In large transformers, having two sets of movable coils balanced one against the other, the counterweight serves merely to draw the primary and secondary coils together in opposition to the repulsion effect. In this case, a decrease in the counterweight is followed by a decrease in the current.

The counterweight attachment is made adjustable because the repulsion exerted by a given current in the coils is not the same at all positions of the coils, being greater when the primaries and secondaries are close together and less when the primaries are separated. When the primaries and secondaries are separated by the maximum distance, the effective force tending to draw them together should be less than when they are in full-load position; that is, when the primaries and secondaries are close together.

For capacities of 100 lamps, or less, there is one primary and one secondary coil, the primary being stationary, and the secondary, or constant-current coil is suspended and so balanced by weights that

the repulsion between it and the primary changes the distance between them with variations of load, the current in the secondary being kept constant.

For capacities of 100, or more, there is one primary and two secondary coils. A separate circuit of lamps may be operated from each secondary, the two circuits being operated at different currents if desired.

The maximum load of each circuit, when operated separately, will be one-half the total capacity of the transformer. However, when it is necessary to operate the two circuits at unequal loads, the load of one circuit being less, and of the other greater, than one-half the rated capacity of the transformer, the coils may be connected together in the multi-circuit arrangement, which will allow loads up to the total capacity of the transformer to be carried upon one circuit.

For capacities of 250, or more, there is one primary and two secondary coils, two circuits being operated from each secondary, thus giving four circuits from the transformer. It is not necessary that the loads on the two circuits from each coil be balanced, and, if desired, the total load can be carried on one circuit alone, provided the insulation of the line is such as to admit of the high voltage which will be introduced. Constant-current transformers are of the air and oil-cooled type. The air-cooled type is surrounded by a corrugated sheet iron, or cast-iron casing with a base and top of cast iron. The oil-cooled type is surrounded

by a cast-iron case, providing ample cooling surface. The working parts are immersed in oil, which assists in conducting away the heat.

The average efficiency of constant-current transformers on full load is 66 per cent.; some of the larger sizes exceeding 100-lamp capacity have a higher efficiency and some of the smaller sizes showing a somewhat smaller average.

CHAPTER XI.

SERIES TRANSFORMERS AND THEIR OPERATION.

The characteristics of the series transformer are not very generally known. It is used in connection with alternating-current ammeters and wattmeters where the voltage of the circuit is so high as to render it unsafe to connect the instrument directly into the circuit and when the current to be measured is greater than the capacity of the instrument.

The transformer consists of an iron magnetic circuit interlinked with two electric circuits. The primary is connected in series with the line, the current of which is to be measured, and the secondary is connected to instruments. It is evident that the meter readings will go up and down with the primary current; though the ratio of the instrument to the primary current may not be the same at all times, any one value of the current will always give the same reading. In well designed transformers the ratio of primary to secondary current is nearly constant for all loads within the designed limits.

In the case of a series transformer with its primary connected to the line and its secondary on open circuit, the primary current will set up a magnetic field in the iron of the transformer, which will cause a drop in voltage across the primary.

The same magnetic flux will also cut the secondary and generate in its winding an e.m.f. whose value is equal to the voltage drop across the primary multiplied by the ratio of the secondary to primary turns. When the secondary is open-circuited the iron of the transformer is worked at a high degree of saturation, which produces an abnormally large secondary voltage. This condition gives rise to serious heating of the transformer as well as great strains upon the insulation.

If the secondary circuit be closed through a resistance there will be a secondary current, which allows a larger resultant flux in the core the less the value of the current, which flux generates the secondary e.m.f. An increase in the secondary resistance does not mean a proportionate decrease in the secondary current, it only means such a decrease in the current as would increase the resulting magnetic flux and secondary e.m.f. sufficiently to maintain the current through the increased resistance. Under ordinary conditions the resistance in the secondary circuit is low, so that the secondary e.m.f. is low and also the resultant magnetic flux.

If the secondary be short-circuited so that there is no magnetic leakage between the windings, and current put on the line, a magnetic flux will be set up in the primary. This flux produces an e.m.f. in the secondary which sets up a current opposed to that in the primary. The result is that the flux threading the windings will be reduced to a value

which will produce a sufficient voltage to establish current through the secondary resistance. Thus the magnetomotive force of the primary current is less than that of the secondary current, by an amount such that the flux produced thereby generates the voltage required to send the secondary current through the resistance of the secondary circuit, the vector sum of the secondary current and the magnetizing current being equal to the primary current.

When the secondary resistance is increased, there will be a decrease in the secondary current which allows a larger resultant flux, which in turn decreases the secondary e.m.f., which increases the secondary current. When a stable condition is reached there is a greater secondary e.m.f. and a less secondary current. In order to determine the characteristics of a series transformer it is in general necessary to know the resistances and reactances of the primary and secondary windings of the transformer and of the external secondary circuit, and the amount and power-factor of the exciting current at the various operating flux densities in the transformer. If no magnetizing current were required, the secondary ampere-turns would be in approximate equilibrium with the primary ampere-turns and consequently the ratio of the primary to the secondary current would be the inverse of the number of turns. In order to attain this ratio as nearly as possible the iron is worked considerably below the "knee"

of the $\mathfrak{B}$-$\mathfrak{H}$ curve, so that very little magnetizing force is required.

The series transformer is worked at about one-tenth the magnetic density of the shunt transformer, due to the fact that a large cross-section of iron is used. It is readily understood that a series transformer differs very much mechanically from a shunt transformer; the latter maintaining

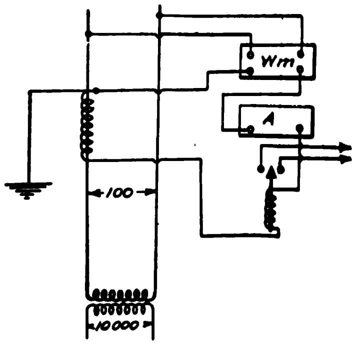


FIG. 77.—Series transformer used in connection with ammeter and wattmeter on single-phase circuit.

a practically constant voltage on the secondary irrespective of the load, while the former must change its secondary voltage in order to change its secondary current.

There are a number of different ways of connecting two or more series transformers to a polyphase system. One or more may be used in connection with alternating-current relays for opera-

ting circuits for overload, reverse current, reverse phase, and low voltage. Some of the connections for this purpose are shown in Figs. 77 to 84.

One series transformer is sufficient for opening the circuit of a single-phase system, and at the same time used in connection with an ammeter and wattmeter as shown in Fig. 77. For three-

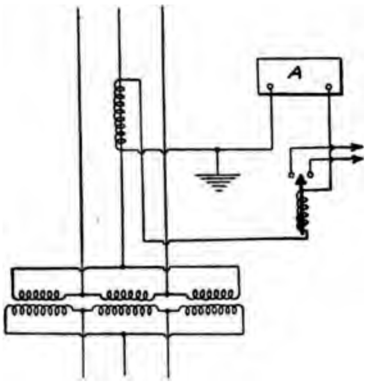


FIG. 78.—Method of connecting a series transformer, ammeter, and relay on a delta connected three-phase system.

phase working, one, two or three series transformers may be used for relays, ammeters and wattmeters. It is often recommended that three series transformers should be used for three-phase systems, but in the majority of cases two are sufficient to give satisfactory results. In Fig. 78 one is shown connected to one leg of a three-phase

delta system. Its secondary circuit being connected through a relay and an ammeter.

In connection with overload relays one series transformer may be used for operating a three-phase system, and when operating three-phase wattmeters, two are all that is required. The connection shown in Fig. 79 will be found to give

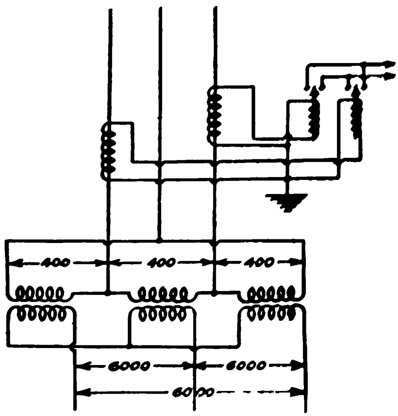


FIG. 79.—Method of connecting two series transformers and relays to a three-phase system.

good results, as each transformer has its own tripping arrangement.

Three transformers are quite common operating together on a three-phase, star-connected system, neutral point grounded or ungrounded.

If all the secondary windings are not arranged in the same direction the phase relations between

one outside wire and the middle wire, and the middle and the other outside wire will be 60 degrees instead of 120 degrees. In order to obtain a phase relation of 120 degrees between each winding, one of the secondary windings must be reversed.

Fig. 80 represents three series transformers with

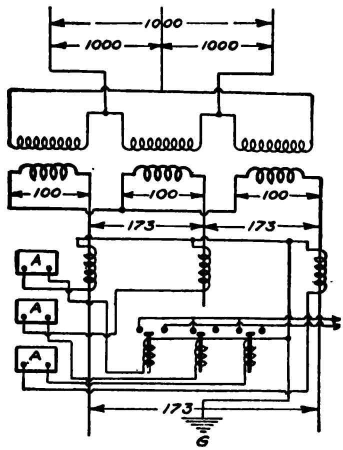


FIG. 80.—Method of connecting three series transformers, three ammeters and three relays on a three-phase star connected system.

all the secondary windings connected in one direction. It makes no difference whether the method of connection be delta or star, it becomes necessary to reverse one transformer with respect to the others when 120 degrees displacement is required. In connection with ammeters it makes

no difference whether the three secondary windings are connected in the same direction or not, as the phase relations do not change the ammeter readings.

A connection very much used where one relay is required, is shown in Fig. 81, in which the series

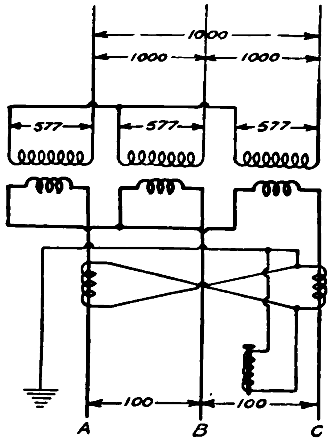


FIG. 81.—Three-phase star arrangement showing two series transformers connected in opposition.

transformers have their opposite terminals connected. The secondary phase relations tend to operate in parallel so that when a current exists in the primary of one transformer a current will also exist in the secondary and relay, but will not be great enough to operate the trip coil. If a short-circuit should occur on any one phase of

the two outside wires *A C*, the secondary will become overloaded and its voltage will rise to a value above that of the secondary of the other transformer; this will tend to reverse the current in the latter transformer, which in turn will allow the primary flux to raise the voltage to the value

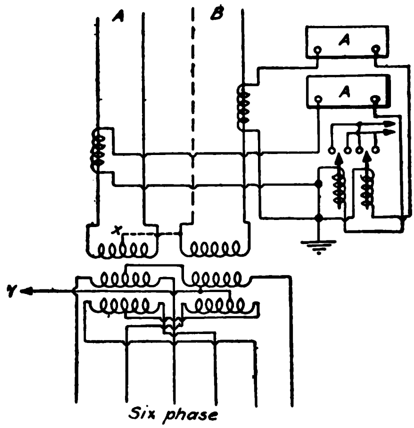


FIG. 82.—Method of connecting two series transformers with instruments and relays to a two or three-phase system inducing six-phase secondary currents.

of the former transformer, this voltage will cause the additional current to overload and operate the relay. This current value will not be twice the current through the two transformers, but will be the algebraic sum of the currents at 120 degrees apart, or $\sqrt{3}$ times the current in each leg. For example: If two series transformers are wound

for 5 amperes on their secondaries with normal current through their primaries, the algebraic sum of the two currents is

$$\sqrt{3} \times 5 = 8.66 \text{ amperes.}$$

Fig. 82 shows a two-phase arrangement of connecting two series transformers for working instru-

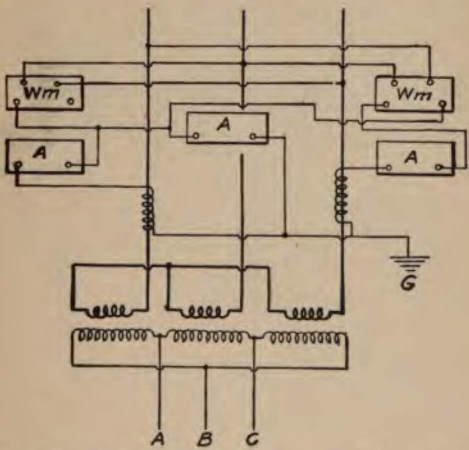


FIG. 83.—Three-phase star arrangement showing two series transformers, two wattmeters, and three ammeters.

ments and relays. It will be noticed in all the connections shown that the secondaries of all transformers are grounded on one side.

In Fig. 82 the system is so arranged that two-phase or three-phase currents will give a six-phase secondary, depending upon the connection made at point *x*. The series transformer connections

are so arranged that the instruments will work satisfactorily with any of the two independent phase currents.

The Y represents the neutral point of the secondary power transformers, and may be used as a

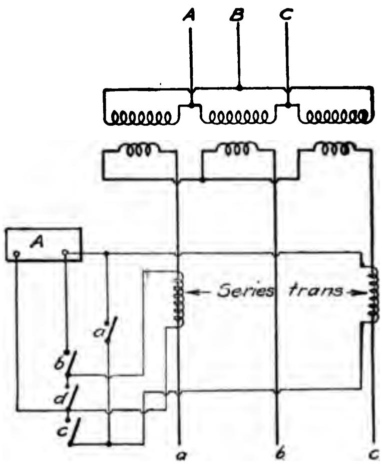


FIG. 84.—Method of connecting two series transformers and one ammeter to a three-phase system, to measure the current in any lead.

neutral wire in connection with a direct-current system of supply.

Another interesting connection is shown in Fig. 83, in which currents are measured in the three phases by the use of two series transformers. The geometrical sum of the currents in the pri-

maries where the two series transformers are installed, is measured by the ammeter shown connected to the grounded side of the transformers. The value obtained is that of the current through the middle wire.

The potential sides of the two wattmeters may be connected to the secondary leads of two shunt transformers; in the figure they are shown connected directly to the mains.

It is also possible to measure three-phase currents with two series transformers and only one ammeter. The arrangement is shown in Fig. 84. To read the current through the transformer on the left, the two switches, *a* and *b*, are closed. To read the current in the middle line, *b* and *c* are closed; the current through the transformer on the right is measured by closing the two switches, *c* and *d*.

When measurements are not being taken it is necessary that the switches, *a* and *d*, should be closed; as the iron of the two transformers is worked at a high degree of saturation, which produces an abnormally large secondary voltage, giving rise to a serious heating of the transformer.

CHAPTER XII.

REGULATORS AND COMPENSATORS.

Potential Feeder Regulators.—Most all regulators are of the transformer type, with their primary windings connected across the lines and their secondary windings connected in series with the circuit the voltage of which is to be controlled.

A type of single-phase feeder regulator is shown in Fig. 85. It consists of a laminated iron ring with four deep slots on its inner surface, in which the primary and secondary windings are placed. The laminated core is mounted on a spindle and so arranged that it can be turned to any desired position by means of a hand wheel. In the position indicated by $C\,C$, the core carries the magnetic flux due to the primary winding, P, in one direction through the secondary winding, S; and in the position indicated by $C'\,C'$ the core carries the magnetic flux due to the primary winding, P, in the other direction through the secondary winding, S. That is, when the core is in the position $C\,C$ the generated voltage in the secondary winding has its highest value. When the core is midway between $C\,C$ and $C'\,C'$ the generated voltage in the secondary winding is zero, and the feeder voltage is not affected. When the core is in the position, $C'\,C'$, the generated voltage in the

secondary winding is again at its greatest value, but in such a direction as to oppose the generator voltage.

On account of the air-gap between the primary and secondary windings, inductive reactance is introduced in the line which requires compensating.

The Stillwell regulator is another type of transformer for raising and lowering the voltage of

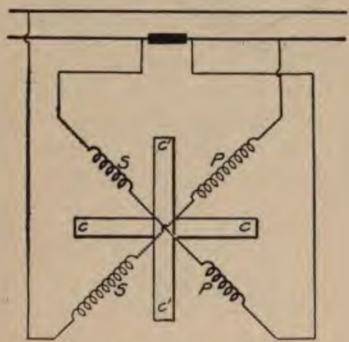


FIG. 85.—Type of single-phase feeder regulator.

feeder circuits. It consists of a primary winding which is connected across the feeder circuit, and a secondary winding in series with the circuit the voltage of which is to be varied.

By means of a switch arm, more or less of the secondary winding may be introduced into the circuit, thus "boosting" by a corresponding amount the voltage of the generator. A reverse switch is provided to which the primary winding

is connected, so that the voltage may be added by moving the switch arm to the right, and subtracted by moving the switch arm to the left.

A regulator built along the lines mentioned above, with an arrangement for connecting the various sections of the secondary winding to a dial switch and reversing switch, is to be seen in Fig.

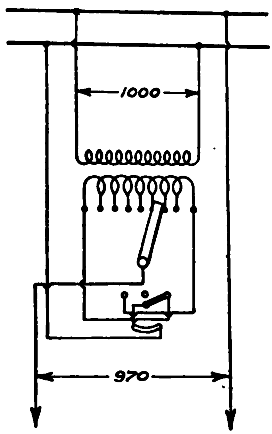


FIG. 86.—Type of Stillwell regulator.

86. The feeder potential can be controlled in the following manner: Starting with the regulator in position of maximum boost, that is, with the dial switch turned to the extreme left as far as it will go, a continuous right-hand movement of the dial switch for two complete revolutions is obtained. During the first revolution the switch cut outs,

step by step, the ten sections of the secondary winding. When the first revolution has been completed, the voltage on the feeder is the same as that of the generator, no secondary winding being included. A further movement of the switch in the same direction automatically throws a reversing switch; and continuing the movement of the dial switch, still in the same direction, the secondary windings are again switched in, step by step, this time with reversed polarity; so that when the second revolution is complete the whole secondary winding is again included in the feeder, but now opposing the voltage of the generator. Thus by one complete movement of the switch, covering two revolutions in one direction the complete range between maximum boost and maximum depression of the feeder voltage is covered.

In incandescent lighting service a potential regulator is particularly valuable. Within the ordinary limits of commercial practice the candle-power of an incandescent lamp will vary approximately 5 per cent. for every 1 per cent. variation in the voltage at the terminals. That is to say, if a 16-c-p. 100-volt lamp be burned at 100 volts it will give about 21 c-p., or at 94 volts about 11 c-p. This fact shows at once the urgent necessity for keeping the voltage of an incandescent system adjusted within inperceptible degrees. A method that has proven somewhat satisfactory with series incandescent systems is shown in Fig. 87. It consists in a primary winding which is connected

across the main lines. Attached to one end of the primary winding is a secondary winding. The secondary voltage, 1, 3, is greater than the primary, 1, 2, by the voltage of the winding, 2, 3. The voltage, 2, 3, is thus added to the primary to form the secondary voltage of the circuit. By reversing the connections of the windings, 2, 3,

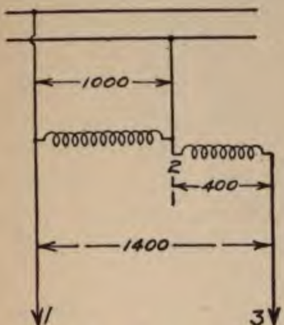


FIG. 87.—Type of regulator used with series incandescent systems.

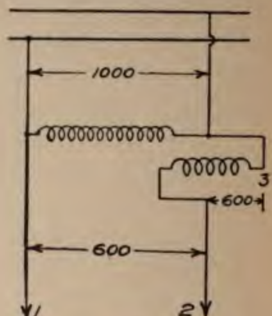


FIG. 88.—Type of series incandescent regulator that reduces the initial primary voltage.

it may be made to subtract its voltage from the primary, 1, 2, in which case the secondary voltage, 1, 3, becomes less than the initial primary voltage; see Fig. 88. Further, by bringing a number of leads from parts of the winding, 2, 3, the secondary voltage, 1, 3, may be increased or decreased step by step as the different leads of 2, 3, are connected to the secondary circuit.

In Fig. 89 is shown the connections of this form of regulator, or compensator. 1, 2, represents the primary winding connected across the circuit. From a portion of the secondary winding, 3, 4, taps are brought to the contact blocks shown in the diagram. The two arms, 7, 8, connect these contact blocks to two sliding contacts, 5, 6. The arms, 7, 8, may be operated by a handwheel, one in direct contact and the other through a gearing,

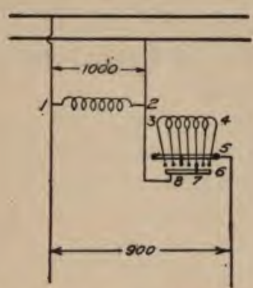


FIG. 89.—Type of voltage regulator.

so that a rotation of the handwheel turns one arm clockwise and the other counter-clockwise.

The secondary voltage of the circuit is that of the primary, increased or decreased by the voltage between the arms, 7, 8. In the neutral position, both arms rest on one central contact block, and the difference of potential between them is zero. In order to decrease the voltage at the lamps, the handwheel is turned to the right, and the voltage decreased step by step, until the final position is

reached with each arm on an extreme contact block. To increase the voltage at the lamps, the handwheel is turned to the left, the two arms being gradually separated on the contact blocks; and the difference of potential between the arms is effected step by step until in the final position, each arm rests on an extreme contact, and the secondary winding is connected into the circuit and its total voltage thus added to the initial voltage of the system. This type of regulator, as will be seen, is in the order of an ordinary auto-transformer with regulating taps arranged on its secondary winding.

For polyphase circuits the system may be regulated by introducing the so-called "induction regulator." This form of regulator has a primary and a secondary winding. The primary winding is connected across the main line, and the secondary winding in series with the circuit. The voltage generated in each phase of the secondary winding is constant, but by varying the relative positions of the primary and secondary, the effective voltage of any phase of the secondary on its circuit is varied from maximum boosting to zero and to maximum lowering. In order to avoid the trouble of adjusting the voltages when each phase is controlled independently, polyphase regulators are arranged to change the voltage in all phases simultaneously. They can be operated by handwheels or motors. When operated by hand, the movable core is rotated by means of a

handwheel and shaft. When it is desired to operate the regulator from a distant point, the apparatus is fitted with a small motor which is arranged through suitable gearing to turn the movable core. The motor may be of the direct-current or induction type, and controlled at any convenient place.

The theory of this form of regulator is described graphically in Fig. 90 in which the voltage of one phase of the regulator is, $e\,o$ = generator voltage or the e.m.f. impressed on the primary: $a\,o$ =

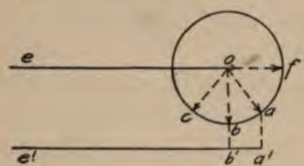


FIG. 90.—Graphical representation of an induction regulator.

e.m.f. generated in the secondary windings, and is constant with constant generator e.m.f.: $b'\,a'$ = secondary e.m.f. in phase with the generator e.m.f.: $e'\,a'$ = line e.m.f., or resultant of the generator e.m.f. and the secondary e.m.f.

The construction of the regulator is such that the secondary voltage, $o\,a$, is made to assume any desired phase relation to the primary e.m.f., as $o\,f$, $o\,b$, $o\,c$, etc.

When its phase relation is as represented by $o\,f$, which is the position when the north poles and the

south poles of the primary and secondary windings are opposite, the secondary voltage is in phase with the primary voltage and is added directly to that of the generator.

The regulator is then said to be in the position of maximum boost, and by rotating the armature with reference to the fields, the phase relation can be changed to any extent between this and directly opposed voltages. When the voltage of the secondary is directly opposed to that of the primary, its phase relation is as represented by *o d* in the diagram, while *o b* represents the phase relation of the secondary when in the neutral position.

The electrical design of the induction regulator is very similar to that of the induction motor. Its efficiency is somewhat higher than the average induction motor of the same rating. The primary winding is placed on the movable core and has either a closed delta or star connection, while the secondary or stationary winding is placed on the stationary core and is an open winding, each section or phase being connected in series with the corresponding phase of the line.

The maximum arc through which the primary moves is 60 degrees for a six-pole and 90 degrees for a four-pole. Induction potential regulators are built for single-phase, two-phase, three-phase and six-phase circuits.

Compensators are used in connection with starting alternating-current motors, and to some ex-

tent they are used in connection with voltmeters in the generating station.

Compensators for starting alternating-current motors consist of an inductive winding with taps. For polyphase work the compensator consists of one coil for each phase *a b c*, Fig. 91 with each coil placed on a separate leg of a laminated iron core. Each coil is provided with several taps, so that a number of voltages may be obtained, any one of which may be selected for permanent connection to the switch for starting the motor.

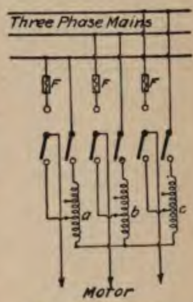


FIG. 91.—Three-phase motor compensator.

When the three-phase winding is used the three coils are connected in star, the line is connected to the three free ends of the coils, and the motor when starting is connected to the taps as represented in Fig. 91.

As it is difficult to predetermine the best starting voltages for each case, for motors rated at from 5 to 15 h.p., taps of 40, 60 and 80 per cent. of the line voltage are provided, according to individual requirements.

The most essential part of the compensator is an auto-transformer, the principle of which has already been explained. The switch for operating the starting compensator is immersed in oil. In starting, the switch moves from the off position to the starting position, where the lowest voltage is

applied to the motor, or the position where the starting torque is the lowest that can be obtained. As soon as the motor speeds up, the switch may be thrown over to the running position; the compensator winding is then cut out and the motor is connected to the line through suitable fuses or circuit breakers. The switch is generally provided with a safety device which is used to prevent the operator from throwing the motor directly on the line, thereby causing a rush of current.

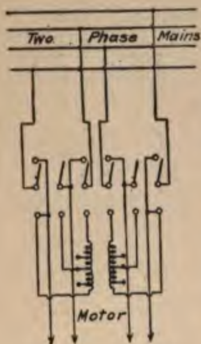


FIG. 82.—Two-phase induction motor compensator.

Compensators are designed to bring the motor up to speed within one minute after the switch has been thrown into the starting position. It is important that the switch be kept in the starting position until the motor has finished accelerating, to prevent an unnecessary rush of current when the switch is thrown to the running position.

In two-phase compensators the line is connected to the ends of the two coils, and the starting connections of the motor to the taps as shown in Fig. 92.

The switch for operating the starting compensator and motor is the same as that used on the three-phase service.

Other designs are used, one of which operates

the compensator as follows: For starting the motor the switch handle moves from the off position to the first starting position, where a low voltage is applied to the motor; then to a second starting position where a higher voltage is applied; and then to the running position, where the motor is connected directly across the line, the compensator being disconnected from the circuit. For stopping, the switch handle is moved to a notch still further along than the running position, the movement of the switch handle being in the same direction as in starting. In the latter position the switch handle is released so that it can be moved back to the off position ready to start again.

The other form of compensator used to indicate the variations of voltage at the point of distribution under all conditions of load without appreciable error between no-load and overload, consists of three parts: a series transformer, a variable reactance, and a variable resistance. The compensator is adjusted to allow for the resistance and inductive reactance of the line. If these are properly adjusted, a local circuit is obtained corresponding exactly with the line circuit, and any change in the line produces a corresponding change in the local circuit, causing the voltmeter always to indicate the potential at the end of the line or center of distribution, according to which is desired. It is well known that the drop in a direct-current circuit is dependent upon the re-

sistance, but in an alternating-current circuit it is due not only to the resistance of the lines, but also to the reactance. The reactance usually causes the drop to be greater than it would if the resistance were the only factor. Therefore, it is necessary that a compensator should give accurately the voltage at the load at all times, whatever may be the current and power-factor.

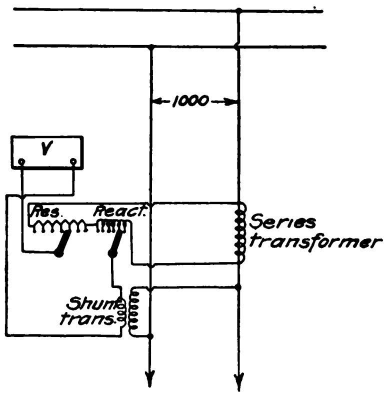


FIG. 93.—Form of compensator used to indicate the variations of voltage at the point of distribution under all conditions of load.

Fig. 93 shows a series transformer in series with the line; and having, therefore, in its secondary circuit a current always proportional to the current in the line. The reactors and resistors are both so wound that any proportion of the winding can be cut in or out of the voltmeter circuit, so modifying the reading of the station volt-

meter that it corresponds with the actual voltage at the point of consumption, regardless of the current, power-factor, reactance, and resistance in the line. For balanced two- and three-phase circuits one compensator is sufficient.

In order to make the voltmeter compensator operation more clear to the reader a practical example is given below. If the drop of potential in the line is, say, 10 per cent. at maximum current, and an e.m.f. of 100 volts is desired to be kept on the lamps at the center of distribution, the voltmeter at the station would have to read 110 volts. By placing in the circuit a compensator, which is designed to give 20 volts at maximum current on the line, and setting the reactance and resistance, 10 of those volts will be in opposition to the voltage of the secondary of the voltmeter transformer, and the voltmeter will read 100 volts, which is the voltage at the center of distribution. By regulating the voltage impressed on the circuit at the station end, so that the voltmeter always reads 100 volts, the voltage at the center of distribution will always be kept constant at 100 volts, no further adjustment of the resistance and reactance being necessary.

CHAPTER XIII.

TRANSFORMER TESTING IN PRACTICE.

In order to determine the characteristics of a transformer the following tests are made:—

1. Insulation.
2. Temperature.
3. Ratio of transformation.
4. Polarity.
5. Iron or core loss.
6. Resistances and I^2R.
7. Copper loss and impedance.
8. Efficiency.
9. Regulation.

Insulation.—The insulation of commercial transformers should be given the following tests:

a. Normal voltage with overload.

b. Double voltage for 30 minutes and three times the normal voltage for five minutes.

c Between primary, core and frame.

d. Between primary and secondary.

f. Between the secondary, core and frame.

The National Board of Fire Underwriters specify that the insulation of nominal 2100-volt transformers, when heated, should withstand continuously for one minute a difference of potential

of 10,000 volts alternating current between the primary and secondary coils and the core.

For testing the insulation of transformers, a high-potential testing set with spark-gap is required. The testing set should, preferably, have low reactance so that the variation in voltage, due to leading and lagging currents, will not be large. The voltages will be practically in the ratio of the turns, and the high-tension voltages may be determined by measuring the low-tension voltages and multiplying by the ratio of transformation. Where an electrostatic voltmeter is available the high-tension voltage is obtained by direct measurement.

In applying insulation tests, it is important that all primary terminals should be connected together as well as all secondary terminals, in order to secure a uniform potential strain throughout the winding. In testing between the primary and secondary or between the primary and core and frame, the secondary must be connected to the core and frame, and grounded.

In making the test, connect as shown in Fig. 94. The spark-gap should be set to discharge at the desired voltage, which may be determined directly by means of test with static voltmeter, or by the spark-gap table giving sparking distances in air between opposed sharp needle-points for various effective sinusoidal voltages in inches and in centimeters.

After every discharge the needle points should

be renewed. The insulation test which should be applied to the winding of a transformer depends upon the voltage for which the transformer is designed. For instance, a 2100-volt primary should withstand a difference of potential of 10,000 volts, and a 200-volt secondary should

SPARKING DISTANCES.

Table of Sparking Distances in Air between Opposed Sharp Needle-Points, for Various Effective Sinusoidal Voltages, in inches and in centimetres.

Kilovolts Sq. Root of Mean Square	Distance Inches	Cms.	Kilovolts Sq. Root of Mean Square	Distance Inches	Cm.
5	0.225	0.57	140	13.95	35.4
10	0.47	1.19	150	15.0	38.1
15	0.725	1.84	160	16.05	40.7
20	1.0	2.54	170	17.10	43.4
25	1.3	3.3	180	18.15	46.1
30	1.625	4.1	190	19.20	48.8
35	2.0	5.1	200	20.25	51.4
40	2.45	6.2	210	21.30	54.1
45	2.95	7.5	220	22.35	56.8
50	3.55	9.0	230	23.40	59.4
60	4.65	11.8	240	24.45	62.1
70	5.85	14.9	250	25.50	64.7
80	7.1	18.0	260	26.50	67.3
90	8.35	21.2	270	27.50	69.8
100	9.6	24.4	280	28.50	72.4
110	10.75	27.3	290	29.50	74.9
120	11.85	30.1	300	30.50	77.4
130	12.90	32.8			

therefore be tested for at least 2000 volts. The length of time of the insulation test, varies with the magnitude of the voltage applied to the transformer, which, if severe, should not be continued long, as the strain may injure the insulation and permanently reduce its strength.

Transformers are sometimes tested by their own voltage. One side of the high-tension winding is connected to the low-tension winding, and the iron, and the transformer operated at a voltage above the normal to give the necessary test voltage. The same test is repeated when the other end of the high-tension winding is connected and the one side disconnected.

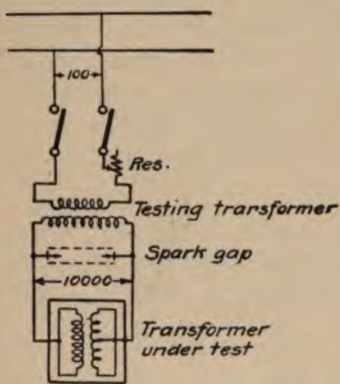


FIG. 94.—Method of connecting apparatus for insulation test.

In making insulation tests great care should be taken to protect not only the operator but others adjacent to the apparatus under test. If it is necessary to handle the live terminals, only one should be handled at a time, and whenever possible, it should be insulated beyond any possibility of the testing set being grounded.

Another insulation test called "over-potential test" is made for the purpose of testing the insulation between adjacent turns and also between adjacent layers of the windings. In applying the over-potential test, the exciting current of a transformer is always increased, but should never be allowed to exceed the full-load current of the transformer.

This test usually consists of applying a voltage three to four times the normal voltage to one of the windings with the other winding open-circuited. If this test is to be made on a 2000-volt winding, at three times its normal voltage, 6000 volts may be applied to one end of the winding in question, or:

3000 volts to a 1000-volt winding,
1200 volts to a 400-volt winding,
300 volts to a 100-volt winding.

In general, this test should be applied at high frequency so that the exciting currents may be reduced. The higher the frequency the less will be the amount of current required to make the test. It is recommended that 60 cycles be the least used, and for 60-cycle transformers 133-cycle currents be applied, and for 25-cycle transformers 60 cycles.

The duration of the over-potential test may vary somewhat with the magnitude of the voltage applied. The test shown in Fig. 95 may be applied for about five minutes.

Temperature.—The temperature or heat test of a transformer may be applied in several ways, all of which are arranged to determine as nearly as possible the working conditions of the transformer in actual service.

Before starting a temperature test, transformers should be left in the room a sufficient length of

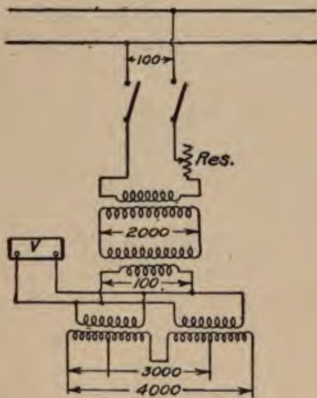


Fig. 95.—Method of connecting transformers and instruments for an over-potential test.

time for them to be affected alike by the room temperature.

If the transformer has remained many hours in a room at constant temperature so that it has reached approximately uniform temperature throughout, the temperature of the surface may be taken to be that of the interior, or internal temperature. If, however, the transformer is

radiating heat to the room, the temperature of the surface will be found to give little indication of the temperature of the interior.

To ascertain the temperature rise of a transformer, thermometers are sometimes used, which give only comparative results in temperature and such measurements are, therefore, useful only in ascertaining an increase in temperature during the heat run. If thermometers are used they should be screened from local air-currents and placed so that they can be read without being removed. If it is desired to obtain temperature curves, thermometer readings should be taken at half-hour intervals throughout the test and until difference between room temperature and that of transformer under test is constant.

In order to determine temperature rise by measurement of resistance, it is necessary to determine first what is called "cold" resistance by thermometer measurements after the transformer has remained in a room of constant temperature for a sufficient length of time to reach a uniform temperature throughout its windings.

The temperature rise by resistance gives the average rise throughout the windings of the transformer, and to obtain average temperature rise of each of the windings, separate resistance readings should be taken of each.

The temperature rise by means of resistance may be determined by the use of the following equation:

$$R = R_0 \, (1 + 0.004 \, t);$$

where R_0 is the resistance at room temperature; R the resistance when heated, and t the rise in temperature. The temperature coefficient of resistance is taken as 0.004 at 25 degrees centigrade. Considering the above equation, the temperature rise corrected to 25 degrees centigrade may be determined in the following manner.

Example: Let room temperature be 20 degrees centigrade, and absolute temperature of transformer 60 degrees centigrade. Ascertain correct temperature rise.

The temperature is apparently $60-20=40$ degrees centigrade, but since the room temperature is 5 degrees lower than the standard requirements, a correction of $0.5\times5=2.5$ per cent. must be added giving a corrected temperature of

$$\frac{100\times2.5\times40}{100}=41 \text{ degrees centigrade}$$

Thus with a room temperature of 20 degrees centigrade the rise in temperature calculated from the above equation should be added by 2.5 per cent., or with a room temperature of 35 degrees centigrade, the rise in temperature should be decreased by 5 per cent.; and with a room temperature of 15 degrees centigrade, the rise in temperature should be increased by 5 per cent., and so on.

If the room temperature differs from 25 degrees centigrade the observed rise in temperature should be corrected by 0.5 for each degree centigrade. This correction is intended to compensate for the

change in the radiation constant as well as for the error involved in the assumption that the temperature coefficient is 0.004, or more correctly, 0.0039, remains constant with varying room temperatures.

To measure the increase of resistance let us take the following example. The primary resistance of a certain transformer is 8 ohms, and at its maximum operating temperature, 9 ohms. Temperature of room during test was 30 degrees centigrade. Ascertain corrected temperature rise.

The primary resistance which is taken at a temperature of 30 degrees centigrade, when referred to temperature coefficient of 0.4 per cent. per degree, represents a rise of $30 \times 0.4 = 12$ per cent. above its value at zero centigrade, which is

$$\frac{8 \times 100}{112} = 7.14 \text{ ohms.}$$

The maximum operating temperature of 10 ohms represents a rise of

$$\frac{(9 - 7.14)\ 100}{7.14} = 26.05 \text{ per cent.}$$

above value at zero, and is equal to

$$\frac{26.05}{0.4} = 62 \text{ degrees centigrade,}$$

absolute temperature.

Deducting from this the room temperature at 30 degrees, the apparent rise = 32 degrees centigrade. Since the room temperature during test

was 5 degrees above standard requirements, a correction of 0.5×5, or 2.5 per cent. must be subtracted, giving a corrected rise of

$$\frac{32 \times 90}{100} = 28.8 \text{ degrees centigrade.}$$

It is well known that high temperatures cause deterioration in the insulation as well as increase in the core loss due to ageing.

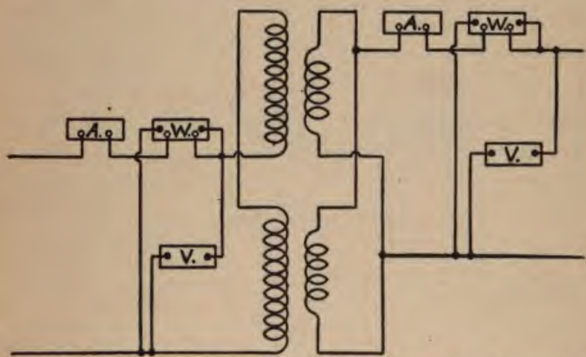


Fig. 96.—Method of connecting apparatus for heat test, known as " opposition " test.

A method of heat testing used to some extent, and known as the "*Opposition*" test, is shown in Fig. 96. In this test two transformers of the same capacity, voltage and frequency are required, and connected as shown in diagram. The two secondary windings are connected in parallel, and the two primary windings are connected in series in such a way as to oppose each other. The

two secondary leads receive exciting current at the proper voltage and frequency, while the primary leads receive a current equal to the desired load current; then the wattmeter in the primary circuit measures the total copper loss, and that in the secondary the total core loss.

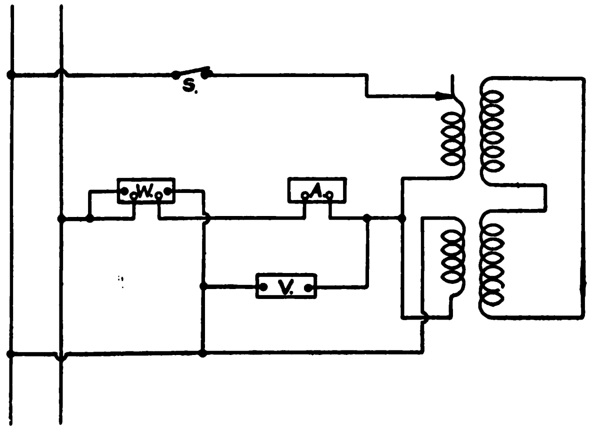


FIG. 97.—Another method of connecting apparatus for heat test known as " motor generator " test.

Another method often used and called the " motor generator test " is shown in Fig. 97. In this test two transformers are used, having their high-tension windings connected together. Proper voltage is applied to the low-tension winding of one of the transformers, and the low-tension winding of the other transformer is connected to the same

source. Then with the switch *s* open, the wattmeter reads the core losses of both transformers, and with *s* closed, it reads the total loss. Subtracting the core loss from the total, the copper loss is obtained. This method requires, as is also the case in the opposition test, that only the losses be supplied from the outside.

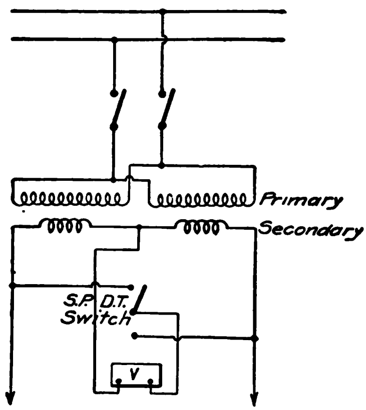


FIG. 98.—Method for ratio of transformation test.

Ratio of Transformation.—The ratio of a transformer is tested when the regulation test is made, it is the numerical relation between the primary and secondary voltage. The ratio of a transformer must be correct, otherwise the service will be unsatisfactory, because the secondary voltage will be too high or too low.

For successful parallel operation, correct ratios

are essential; otherwise cross-currents will be established through the windings.

A method of ratio test is shown in Fig. 98, where the primary of the transformer under test is in parallel with the primary of the standard ratio transformer, and the two secondary windings connected in series.

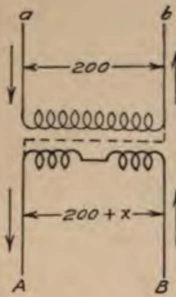


FIG. 99.—Simple method for testing the polarity of transformers.

Polarity.—The most simple method for testing the polarity is to connect the primary and secondary windings of the transformer in parallel, placing a fuse wire in series with the secondary winding. If the transformers are of opposite polarity the connection will short-circuit the one transformer on the other, and the fuse will blow. Many burnouts are due to wrong connections.

Transformers are generally assembled so that certain selected leads are brought out the same in all transformers of the same type. See Fig. 99.

The primary terminal (a) should be of opposite polarity to the secondary terminal (A). If we apply 200 volts to the primary, $a\ b$, of the transformer, the voltage between $a\ B$ should be greater than the voltage applied to $a\ b$, if the transformer is of the correct polarity, or less if of opposite polarity.

Iron or core loss.—The core loss includes the hysteretic and eddy-current losses. The eddy-current loss is due to currents produced in the laminations, and the hysteretic loss is due to molecular friction. The core loss remains practically constant at all loads, and will be the same whether measured from the primary or secondary side, the exciting current in either case being the same per cent of the full-load. The economical operation of a lighting plant depends in a large measure on the selection of an economical transformer. An economical transformer is seldom the one of lowest first cost, nor is it necessarily the one having the smallest full-load losses. It is the one which has the most suitable division of losses for the service for which it is to be used.

The lower the frequency the greater will be the iron loss. In ordinary commercial transformers a given core loss at 60 cycles may consist of 65 per cent. hysteresis and 35 per cent. eddy-current loss, while at 125 cycles the same transformer may have 50 per cent. hysteresis and 50 per cent. eddy-current loss. The core loss is also dependent upon the wave-form of the applied e.m.f. A flat top wave gives a greater loss than a peaked wave and *vice versa.*

With a sinusoidal wave of e.m.f. applied on a transformer, the exciting current is distorted, due to the effect of hysteresis. If resistance is introduced into the primary circuit, however, the exciting current wave becomes more sinusoidal

and the generated e.m.f.-wave more peaked, the effect of these distortions tending to reduce the exciting current and core loss. Since the magnetic density varies with the voltage and inversely with the frequency, an increase in voltage applied to the transformer causes an increase in core loss, while an increase in frequency results in a corresponding decrease in core loss.

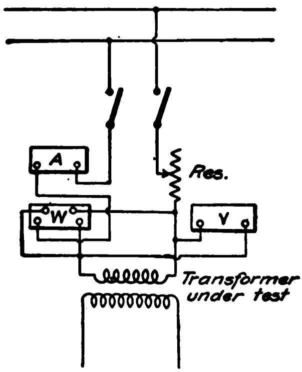


FIG. 100.—Iron or core loss transformer test.

Of the several methods in use for determining core loss, the following method is the simplest to apply and gives very accurate results. See Fig. 100.

Resistances.—The resistance of the primary and the secondary of a transformer may be determined by several different methods, the most common of which are "fall of potential" and "wheatstone bridge" methods. For commercial use the most

satisfactory method is the fall of potential. In this method the resistance may be determined by Ohms law:

$$\text{Resistance} = \frac{\text{Volts}}{\text{Amperes}}.$$

The measurement requires continuous current and a continuous-current voltmeter and ammeter. With the connection shown in Fig. 101, assume, for example, the ammeter reading to be 2.5 amperes, and voltmeter reading to be 11 volts. What is the resistance of coil?

The resistance of voltmeter used in test is 500 ohms, and the temperature of transformer coil is 30 degrees centigrade. Therefore, current taken by voltmeter at 11 volts is,

$$\frac{11}{500} = 0.022 \text{ amp.}$$

Current in transformer coil $= 2.5 - 0.022 =$ 2.478 amp.

The ammeter reading includes the current in the voltmeter, and in order to prevent error the resistance of the voltmeter must be much greater than that of the resistance to be measured.

Resistance of transformer coil at 30 degrees centigrade is,

$$\frac{11}{2.478} = 4.48 \text{ ohms.}$$

It is important that measurements be taken as quickly as possible, especially if the current be near the full-load values, and it is equally important in all cases that the voltmeter needle be at rest before the observation be taken, otherwise the values obtained will not be reliable. It is possible to have a current of sufficient strength to heat the coil so rapidly as to cause it to reach a

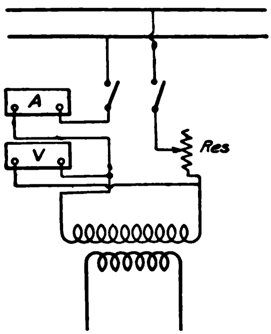


FIG. 101.—Method of finding the resistance of a transformer.

constant hot resistance before the measurement is taken. The resistance of the transformer coil at 25 degrees centigrade, which is the temperature coefficient of 0.42 per cent. per degree from and at zero degrees centigrade, is,

$$\frac{4.48\times 100}{(0.42\times 5)+100}=4.39 \text{ ohms.}$$

If the temperature of windings is different for each observation, then resistance must be calculated for each and the average taken. If the temperature of the windings is the same for all observations, then the average voltage and current may first be determined and the resistance calculated from the average values.

Copper Loss and Impedance.—When a transformer is delivering power, copper loss takes place, varying as the square of the current. It is due to the resistance of the windings and to the eddy currents within the conductors themselves.

The copper loss may be measured at the same time as the impedance-drop measurement by introducing a wattmeter as shown in Fig. 102. It may also be calculated from currents through conductors and resistance of conductors, as follows:

$$P = I_1^2 R_1 + I_2^2 R_2, \text{ in watts,}$$

wherein P is the power lost; I_1, the primary current; I_2, the secondary current; R_1 the primary resistance; and R_2 the secondary resistance.

The impedance in alternating circuits is similar to resistance in continuous circuits. That is to say, the expression

$$I = \frac{E}{R} = \text{Current} = \frac{\text{e.m.f.}}{\text{Resistance}}$$

for continuous circuits is replaced in alternating-current circuits by the equivalent expression,

$$I = \frac{E}{\sqrt{R^2 + (X^2)}} = I = \frac{\text{e.m.f.}}{\text{Impedance}}$$

where I is the current; E the impressed e.m.f.; X the reactance; and R the resistance of the circuit.

The impedance is made up of two components at right angles to each other. (Reactance and Resistance). It is expressed as follows:

$$\sqrt{R^2+X^2}$$

Reactance may be inductive, X_s, or condensive X_c;

$$X_s = 2\pi f L \text{ and } X_c = \frac{1}{2\pi f C};$$

wherein f is the frequency in cycles per second; L is the inductance in henrys; and C is the capacity in farads.

The impedance of a transformer is measured by short-circuiting one of the windings, impressing an e.m.f. on the other winding and taking simultaneous measurements of voltage and current, see Fig. 102.

The impedance voltage varies very nearly with the frequency. In standard transformers the impedance voltage varies from 2 to 6 per cent., depending upon the size and design of the transformer.

Efficiency.—The efficiency of a transformer is the ratio of its net output to its input. The output is the total useful power delivered and the input is approximately the total power delivered to the primary; and consists of the output power

plus the iron loss at the rated voltage and frequency, plus the copper loss due to the load delivered.

Example: Find the full-load, and half-load efficiency of a 5-kw., 2000 to 200-volt, 60-cycle transformer having an iron loss of 70 watts, a primary resistance of 10.1 ohms, a secondary resistance of 0.066 ohms.

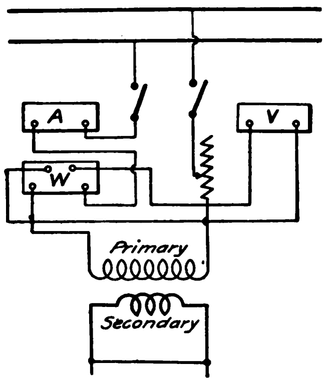


FIG. 102.—Testing the impedance and copper loss of a transformer.

The efficiency of the transformer under consideration is as follows:

Full Load:

Primary $I^2 R$	63 watts
Secondary $I^2 R$	42 watts
Core loss	70 watts
Total Losses	175 watts

Output = ...5,000 watts
Input = 5,000 + 175 ....5,175 watts

$$\text{Full load eff.} = \frac{5{,}000}{5{,}175} = 96.6 \text{ per cent.}$$

Half Load:

Primary and Secondary ....26 watts
Core loss...........................70 watts

Total Losses.................96 watts

Output = ...2,500 watts
Input = 2,500+96.................2,596 watts

$$\text{One-half load Eff.} = \frac{2{,}500}{2{,}596} = 96.2 \text{ per cent.}$$

It will be noted that the iron loss remains constant at all loads but the copper loss varies as the square of the load current. The copper loss remains the same in all transformers of a given design and size, it is, therefore, only necessary to make these tests on one transformer of each rating and type.

Regulation.—The regulation of a transformer with a load of given power-factor is the percentage of difference of the full load and no load secondary voltages with a constant applied primary voltage. It may be ascertained by applying full load to the transformer and noting the secondary voltage, then removing the load and noting the secondary open-circuit voltage.

The secondary voltage drop will be very much greater with an inductive load, such as induction motors or arc lamps, than it will be with incandescent lamps.

The regulation can be determined by direct measurement or calculation from the measurements of resistance and reactance in the transformer. Since the regulation of any transformer is only a few per cent. of the impressed voltage, and as errors of observation are liable to be fully one per cent., the direct method of measuring regulation is not at all reliable. By connecting the transformer to a circuit at the required voltage and frequency, using a lamp load or water rheostat on the secondary the regulation may be determined. This method, is, however, unsatisfactory, and much more reliance can be placed on the results of calculation.

Several methods have been proposed for the calculation of regulation, and the following is the most accurate for inductive and non-inductive loads.

For inductive loads:

$$\begin{aligned}\%\text{ regulation} &= \%\, X \sin\theta + \%\, I\,R \cos\theta.\\ &= \%\, E_x \sin\theta + \%\, E_r \cos\theta.\end{aligned}$$

Per cent. E_x = the per cent. reactance drop.
Per cent. E_r = per cent. total resistance drop.
θ = the angle of lag of load current delivered.

Example: Find the regulation of a transformer with a reactance drop of 3.47 per cent., and a resistance drop of 2.0 per cent. when delivering a load to a circuit having a power-factor of 87 per cent.

The $\cos\theta = 0.87$ is 30 degrees. The sine of the

angle of 30 degrees is 0.5. Then from the above formula:

Per cent. regulation $= 3.47 \times 0.5 + 2 \times 0.87 = 3.48.$

For non-inductive loads:

$$\% \text{ regulation} = \% \, I R - \frac{\% \, IX - 2 \, IX i}{200}$$

Per cent. $I R$ = per cent. resistance drop.

$\% \, X = \sqrt{\% \text{ impedance drop}^2 - \% \text{ resistance drop}^2}$
$= \%$ reactance drop.

$i = \sqrt{\% \text{ exciting current}^2 - \% \text{ iron loss current}^2}.$
The iron loss.

For non-inductive load $\theta = 0$, $\sin \theta = 0$, $\cos \theta = 1$, and we have

$$\% \text{ regulation} = \% \, E_r$$

The above formula is practically correct for small values of angle θ and the error becomes greater as θ increases.

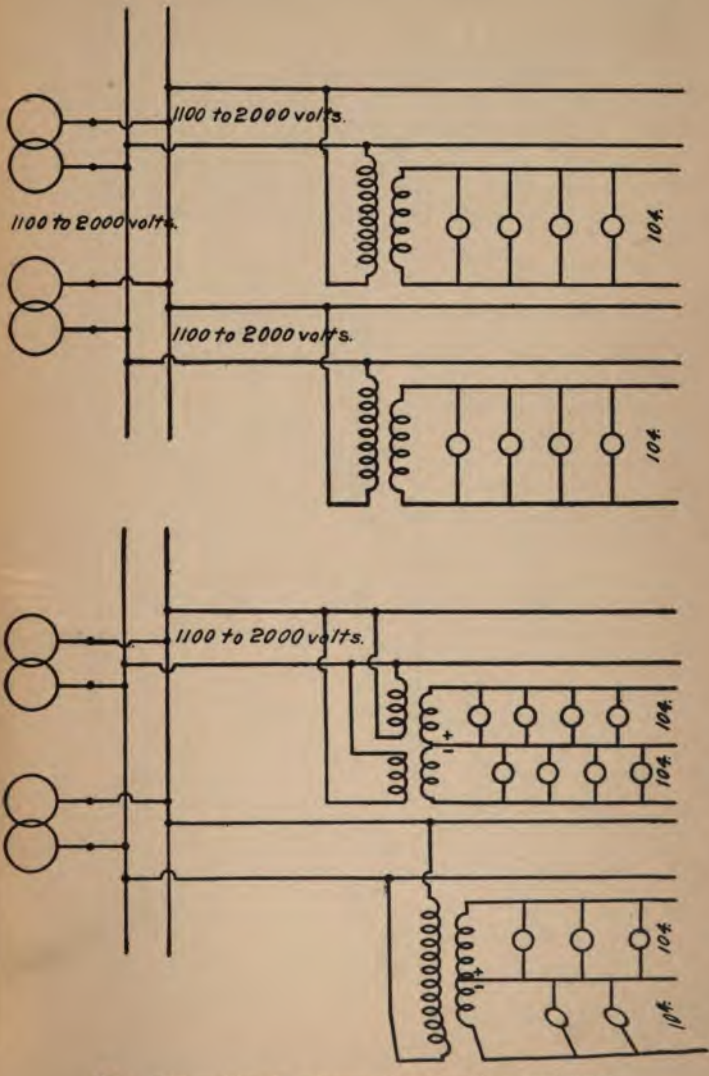


FIG. 103.—Single-phase distribution systems.

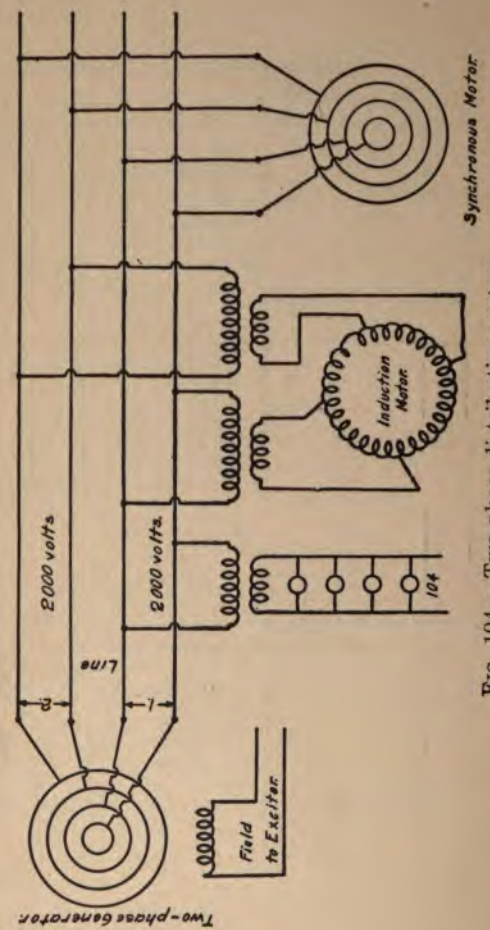


FIG. 104.—Two-phase distribution system.

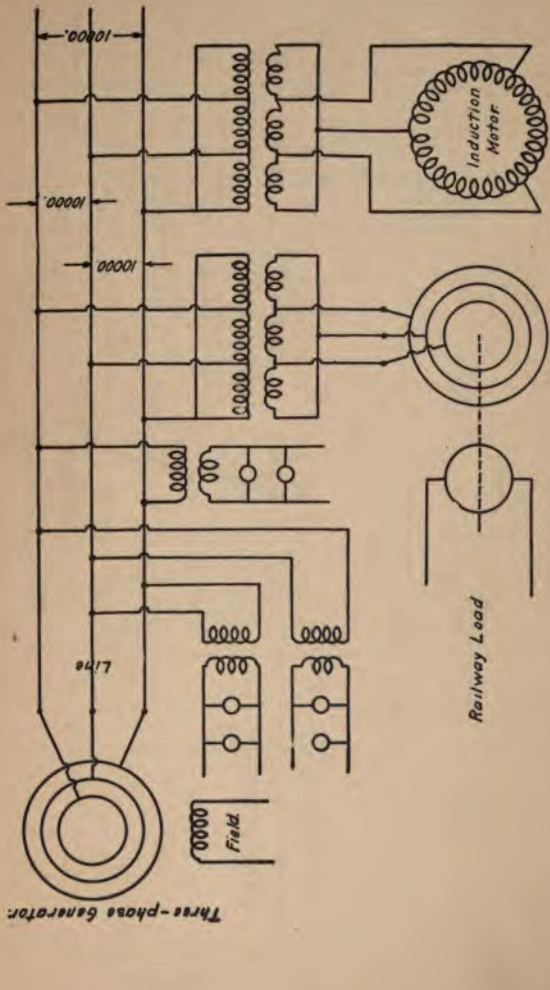


FIG. 105.—Three-phase distribution system.

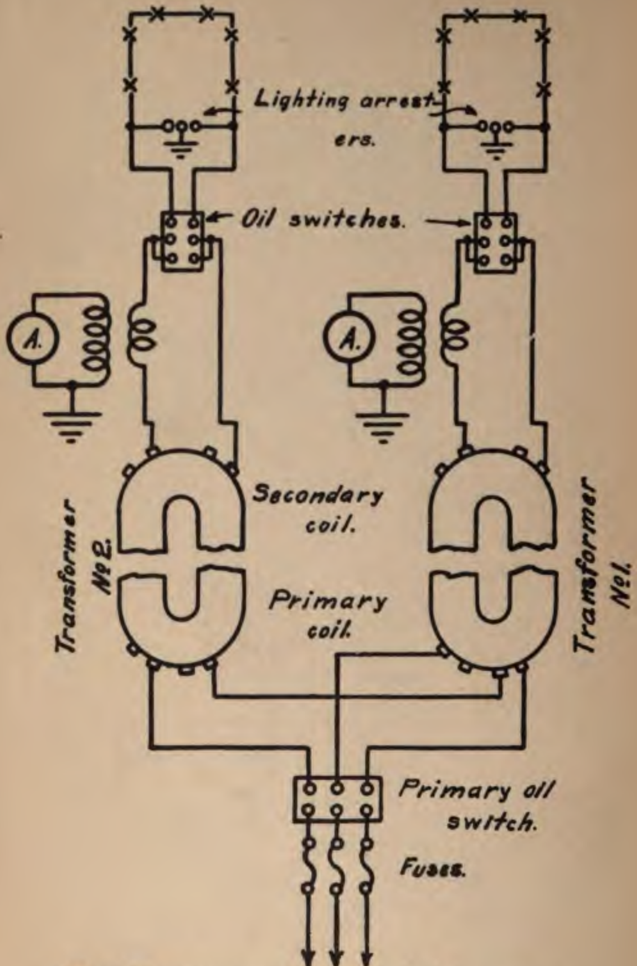


FIG. 106.—Constant-current arc lighting system.

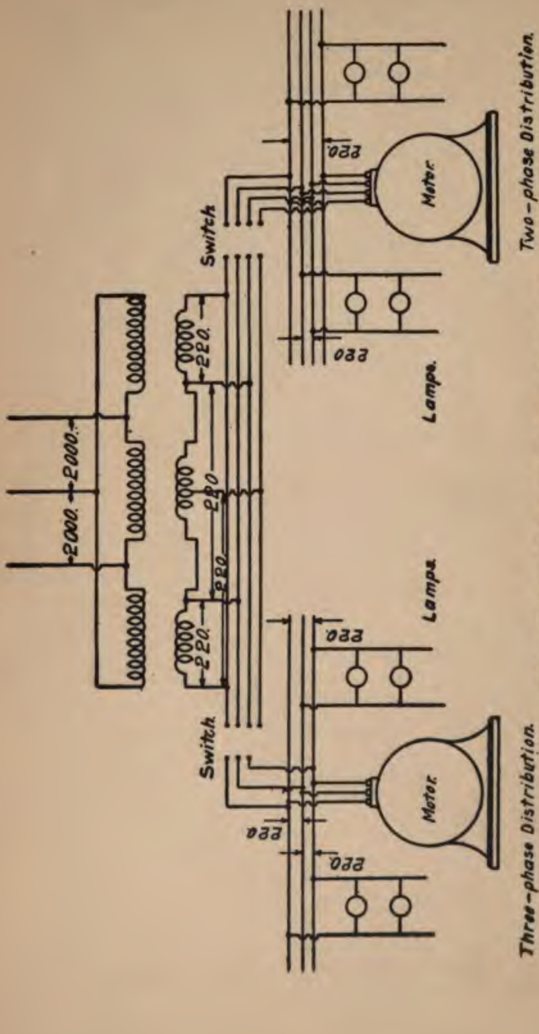


FIG. 107.—Taylor three-phase two-phase system.